AFWAL-TR-88-3055

AD-A215 127

FINITE ELEMENT MODELS FOR SUPPORTABILITY OF UNITED STATES AIR FORCE AIRCRAFT STRUCTURES

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July 1988

Final Report for Period Jul 87 to Jan 88

Approved for public release; distribution unlimited

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS None
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) PDA - TR-5540-00-01	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFWAL-TR-88-3055
6a. NAME OF PERFORMING ORGANIZATION PDA Engineering 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Flight Dynamics Laboratory (AFWAL/FIBR) Air Force Wright Aeronautical Laboratories
6c. ADDRESS (City, State, and ZIP Code) 2975 Red Hill Avenue Costa Mesa, CA 92626	7b. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB, OH 45433-6533
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F33615-87-C-3237
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
65502F	3005	30	99

11. TITLE (Include Security Classification)

Finite Element Models for Supportability of United States Air Force Aircraft Structures

12. PERSONAL AUTHOR(S)
HEINZ, Lee Anne

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Phase I	FROM 870701 TO 880101	880129	88

16. SUPPLEMENTARY NOTATION
This is a Small Business Innovation Research Progress Report, Phase I

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Finite Element Modeling, Analysis, Structures, Aircraft, Database

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The purpose of this Phase I effort is to determine if a centralized database system for finite element models (FEM) of USAF aircraft is feasible. AF personnel were surveyed and interviewed to determine if there was a need for such a system and the characteristics that such a system should possess. The results of this study show that a FEM database system for storage and retrieval of FEM data is warranted. A centralized database system, as proposed in this report, could provide cost savings benefits. The concept of centralized database system need not be limited to aircraft structures. Other types of structures and various organizations which use FEM could benefit from implementation of such a system.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Vipperla B. Venkayya	22b. TELEPHONE (Include Area Code) (513) 255-6992 22c. OFFICE SYMBOL AFWAL/FIBRA

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ACKNOWLEDGEMENTS

Appreciation is extended to the personnel of the Air Force Logistics Command and Air Force Systems Command who participated in the survey on which this Phase I study is based.

The assistance of the Technical Program Monitor, Dr. V. B. Venkayya of the AFWAL/FIBRA, in the conduct of this Phase I study is warmly acknowledged.

BACKGROUND STATEMENT

This study was conducted by Lee Anne Heinz, a Member of the Technical Staff, Solid Mechanics Department, Materials and Structures Technology Division and an experienced finite element analyst. An adjacent operating division of PDA, the PATRAN Division, develops and markets PATRAN-II™, an MCAE software system. Many elements of PATRAN-II™ are relevant to the needs of the centralized FEM system studied in this report. It is recognized that other MCAE software systems exist and are utilized by some Air Force organizations. While this study utilizes our knowledge of the PATRAN-II™ system, it also reflects the fact that any centralized FEM system must be compatible with a variety of MCAE software systems.

1.0 SUMMARY AND CONCLUSIONS

A study was conducted of the use of finite element models (FEM) and finite element analyses (FEA), the methodologies employed in acquiring these FEMs, and estimated costs (direct, indirect and missed opportunities) of the current FEM acquisition system in representative Air Force organizations. This study was based on a written survey of and follow on telephone interviews with ten (10) Air Force Logistic Command and Air Force System Command organizations associated with aircraft systems. The results of this study are presented in context of the growing usage of mechanical computer-aided engineering (MCAE) technology in private industry, in general, and the aerospace industry, in particular.

Estimates of the costs of the present dispersed system of FEM acquisition are on the order of at least $5M annually. Acquisition costs of contractors' FEMs, largely a reflection of documentation costs, and costs associated with internal duplication of FEM development appear to be on the order of $2-3M. Less defined costs associated with an inefficient dispersed system, such as unnecessary education/training and search/information activities, appear to be on the order of $1M. The largest costs, and the poorest defined, are unnecessarily incurred testing costs for lack of appropriate FEM/FEA. These are strongly believed to be in excess of $1M per year and may be on the order of $10M per year.

PDA Engineering proposes a database approach to a centralized FEM system. A preliminary system is defined in this study and user methodology is illustrated through a typical FEM/FEA test case. Tangible benefits of such a system are defined as a standardized model and documentation format, reduced cost and effort for determining availability of existing FEMs, reduced cost and effort in procuring FEMs from contractors, facilitated installation of the FEM onto a given computer system, reduced "ramp-up" time bringing the FEM on line, enhanced communication between Air Force organizations, automated FEM documentation capability, reduced training time on FEMs, reduced cost of obtaining design information, and timely acquisition of design information. Startup costs (both hardware acquisition, software development and manpower) are estimated at less than $2M a year and annual operating costs are in the range of $350K to 700K.

This study indicates a need exists for a centralized FEM system which would return substantial benefits to the Air Force. The costs incurred by the present dispersed system and the esimated costs associated with a central FEM system suggest a substantial return on initial investment and a dramatic annual cost savings with a significant improvement in operational performance.

2.0 INTRODUCTION

Presently the United States Air Force (USAF) purchases aircraft from various contractors. The contractors must do both testing and finite element analysis (FEA) to prove that their aircraft meet the design specifications. The results of the finite element analyses are usually delivered to the Air Force (AF) in stress report format and the finite element models (FEM) used to obtain these results are usually not required by contract. It has been the AF's experience, however, that throughout the course of an aircraft's lifetime, these models can be used to address a variety of applications such as repair, maintenance, or design modification. Even though the AF initially pays at least part of the FEM costs, which may be on the order of a million dollars for their development, additional monies must be paid when the AF wishes to obtain these models along with supporting documentation. It is not sufficient to simply require these models as contract items because of the variety of modeling approaches that are utilized and the longevity of the aircraft system's useful life which maybe 20 to 30 years or more. Specifications for documentation and model format must exist in order to make the models usable to the Air Force.

Even deliverable specifications for FEM may not be enough to insure the most cost efficient use of AF funds. In some instances, even after the models have been "repurchased" from the contractors, their use is limited to the organization which purchases it because of the size of the AF and problems in communication between AF organizations . For example, finite element models which are of use to a specific Air Logistic Center (ALC) may be of little use to personnel in another Air Logistic Center because each ALC is responsible for a specific system or systems. However, organizations of the Air Force Systems Command (AFSC) may have need for a model from the ALC or vice versa and may not be aware of its existence or may not be able to obtain it in a usable format.

There is an increasing use of FEA methods within the Air Force. Consequently, there is a need to address the feasibility of organizing a central function to obtain, modify, evaluate, certify and apply FEM in an efficient way throughout the USAF. Key issues for such a feasibility study include the need for deliverable FEM specifications (i.e., documentation and model format), methods of communicating FEM information among AF organizations, and the cost-benefits associated with a centralized system.

In this Phase I program, PDA conducted a survey of AF organizations to obtain information on these key issues. Preliminary estimates were made of the potential cost-benefits that would result from the establishment of a centralized system. Finally, a preliminary design concept and implementation methodology were formulated for the centralized system, based upon a database management system.

This Phase I effort addressed these issues by examining the methodology used in acquiring and employing finite element techniques in ten organizations throughout the USAF. Five ALC and five AFSC organizations were selected for this study. The organizations surveyed and interviewed represent a broad cross-section of responsibilities ranging from flight testing to research and development of finite element software. The information gathered in this effort formed the basis for recommendations for AF finite element model information standards. It also was used to determine if it is feasible to develop a centralized function which will obtain, store, verify, and distribute finite element models throughout the Air Force.

Quantification of the cost-benefit issue is strongly dependent upon both current usage of FEA methods within the USAF and their rate of growth. Both parameters, in large part, reflect the overall trends in computer-aided engineering within the United States. The approach taken was to estimate a present net value based on current activities and extrapolate a future value based on trends in CAE activities. This valuation implicitly incorporate the worth of positioning the USAF for future CAE requirements based on the potential capabilities of a centralized system.

Database management systems are becoming a widely accepted method for handling large quantities of information. They are currently used in industry to facilitate information processing which range from personnel records to high technology material properties. The applicability of such an approach was explored in this effort. Giving the development of a centralized system, there will be a large amount of finite element model information to process. A properly designed database system could provide easy storage, retrieval, and query capabilities about finite element models. Searching and cross-referencing capabilities could provide a quick and easy check of availability and applicability of existing models.

3.0 TRENDS IN COMPUTER-AIDED ENGINEERING

There are a number of trends in aircraft systems and computer-aided engineering (CAE) which must be considered to place this Phase I study in proper perspective. The most significant trends are tabulated in Table 3.1. These trends are listed in probable order of near-term to long-term impact.

Although critical to evaluating the need for a centralized FEM system, the first two trends involve expertise outside the preview of this present study and will not be elaborated upon. The other trends, equally important, are illustrative of the growing use of computer-aided engineering and provide additional insights as to how a centralized FEM system could ultimately be utilized.

The Growing Use of CAE - The trends toward use of analytical tools for evaluating design decisions is growing rapidly. Per Dataquest:

TABLE 3.1

TRENDS IN AIRCRAFT SYSTEMS AND CAE

ASPECT	TRENDS
Aircraft	Increasing in cost and complexity
Aircraft Engineering	Increasing reliance on analysis as a complement to testing.
CAE	Increasing use by a broader range of engineering skills.
CAD/CAE/CAM	An Integration of Computer-Aided Design, Computer-Aided Engineering and Computer-Aided Manufacturing Technologies.
Solids Representation	The use of CAE tools to build 3D models from 2D drawings.
Engineering Tomography	The coupling of advanced NDE Methods with CAE techniques to achieve quantitative NDE capabilities.
Artificial Intelligence/ Expert Systems	The application of AI/ES to CAE

"Mechanical computer-aided-engineering (MCAE) is moving into center stage as a primary contributor in the evolution of CAD/CAM"[1].

"Because MCAE technology is changing the way that the world designs its products, it must be considered by every major manufacturing corporation. The ability of a company to remain profitable will depend more and more on its ability to effectively use MCAE technology. MCAE is a major key to higher corporate profitability"[1].

Two factors are driving the growth of MCAE:

1. Engineering Workstations
2. User-Friendly Analysis Packages

The use of engineering workstations (one person/one computer) is the fastest growing trend in CAE. The economics of scale and efficiencies of allowing an engineering community to communicate electronically is a driving force behind this workstation growth. Dataquest states that there are 639,000 U.S. engineers and technical professionals and 88,900 workstations installed in 1986. An evaluative perspective might permit us to say 14% have their own workstation. In 1991 Dataquest predicts there will be 684,000 U.S. engineers and technical professionals and 333,000

workstations. From our evaluative perspective this means 49% will have their own workstations. The rapid growth in computational capability and the subsequent proliferation of powerful, relatively inexpensive engineering workstation technology has made easily accessible to a wide body of engineers the needed computer capability to conduct sophisticated FEA studies. This indicates not only a substantial growth in the number of engineering workstations but also a considerable increase in electronic communication. This increase in electronic communication is the basis of the integration trend to be discussed below.

User-friendly analysis packages is the second factor driving this trend. The introduction of graphics preprocessors and postprocessors has reduced the requirement to be fully versed in all the details of a sophisticated finite element code to complete an analysis. This has permitted experienced analysts some freedom in choosing various analysis codes to be employed for a given problem. This has also allowed the less experienced engineer to conduct analyses without being completely guided by an experienced engineer. The use of FEA methods was once the province of only the most highly trained engineers. The concurrent development of more "user-friendly" and "self-instructional" analysis programs has greatly expanded and is rapidly increasing the number of engineers who employ FEA methods.

The Integration of CAD/CAE/CAM - Earlier in the decade, these disciplines were viewed as distinct and relatively uncoupled disciplines. It is now recognized that maximum efficiency in development and optimum utilization of resources results from the integration of these disciplines through the use of appropriate hardware and software. This trend is being paced by the aircraft industry and, not only is it pertinent to development and production of aircraft (a/c) systems, it ultimately will impact their maintenance, repair and modification.

"The full benefit of CAD/CAM will not be realized until a fully integrated solution can be implemented with complete access by all involved"[1]. Dataquest's 1987 evaluation of the CAD/CAM industry continually stresses communication (integration) of design data as one of the top concerns of CAD/CAM users across industry boundaries.

Designers require timely input from engineers/analysts to cost effectively implement changes to their designs. Dataquest highlights this fact with the results of a study conducted by British Aerospace. The results demonstrate the relative cost of implementing a design change as a function of the stage in the design process:

- In drawing board stage - $1
- In design checking - $10
- In process planning - $100
- In Manufacturing Engineering - $1,000
- In final production - $10,000
- After field failure - $100,000 or more

The key to an efficient design process today is the ease of electronic transfer of design information between organizations. Dataquest refers to this facilitated transfer of information as access.

"The issue of access is critical to the future of MCAE and CAD/CAM in general. Every time an interface is created between manual methods and automation, an inefficiency is introduced. Hopefully, the islands of automation more than compensate for the overhead of a partially automated process. The complete benefit of design and manufacturing automation cannot be realized until everyone with a need has ready access.....(to the design information)".[1]

This trend toward integration is prominent in both the government and the private sector. The Dept of the Navy has issued a Request for Proposal [2] estimated to exceed one billion dollars for a CAD/CAE/CAM system that will be integrated vertically, across software applications as well as horizontally across NAVY system commands. NASA has a similar requirement for the space station program[3].

The private sector has been aggressively pursuing this issue also. PDA is currently under contract with a major oil company to design and develop a system to integrate this company's "in-house" analysis codes and provide one common user-interface for all users[4]. PDA is also involved in discussions with other organizations to provide similar capabilities.

In estimating the worth of the proposed centralized FEM system, the value of the potential integration capabilities should be considered. Many of the maintenance and modification activities on an aircraft system are conducted by Air Force organizations which are often not able to access information from the aircraft system manufacturer. The manufacturer's design group, which developed the a/c system, will most likely have been disbanded before Air Force modification activities are begun. The appropriate time to obtain this design information is during the execution of the original a/c system development contract. Obtaining and storing all of this design information is well beyond the scope of the centralized FEM system proposed under this solicitation, but a properly designed centralized FEM system will facilitate future expansion to permit all organizations access to a/c system design information via an electronic transfer capability. This centralized FEM system will position the Air Force for a efficient upgrade to a horizontally and vertically integrated CAD/CAE/CAM system.

<u>Solids Representation</u> - A relatively specific application of FEM technology, this trend is a reflection that the engineering world is transitioning from two-dimensional presentations of information to three-dimensional presentations. Consequently, there is a growing use of technologies that can construct three-dimensional representations (e.g., solids, FEMs) from 2-D images such as engineering drawings.

Engineering Tomography - A term, believed coined by PDA Engineering, which reflects the coupling of advanced non-destructive evaluation (NDE) technologies, such as tomographic characterization methods, with advanced CAE methods to provide a quantitative, NDE means of determining the behavior of structural components and systems. Tomographic NDE methods, such as radiography (CT) and nuclear magnetic response (NMR), provide a means by which material characteristics can be spatially determined (i.e., in 3D) on a non-intrusive basis. Through the use of testing programs and databases, these NDE-determined characteristics can be correlated with properties of the material system. Concurrently, advanced CAE methods can be used to construct 2D and 3D images (i.e., models) from the 2D NDE scans; convert these images into finite element models; and superimpose the NDE-deduced material properties spatially into these FEMs. The result is the ability to predict the response of components or systems, based on "realistic" properties, to environmental loads. The development of ET is in its infancy but it has major potential to affect the use of engineering system. This need is well recognized by the USAF in its support of this technology [5,6]. FEM is central to ET.

Artificial Intelligence/Expert Systems - There is a small, but growing, use of AI/ES in CAE. Examples pertinent to this study range from the use of ES in the development of finite element models [7] to the use of ES to predict the properties of composite material systems for use in FEA [8]. Given the emphasis placed on the need to develop AI/ES technology in the FORECAST II study [9], it is to be expected that these activities will have a significant impact on the use of FEA methods and FEMs by the USAF in decades to come.

Figure 3-1 summarizes the major conclusion to be derived from this discussion of trends, namely that any assessment of the cost-benefits associated with a centralized system involving FEMs must reflect the growth rate that is to be expected, based on the current trends in growth of CAE, in general, and FEA, in particular.

4.0 PHASE I TECHNICAL APPROACH

PDA's original Phase I proposal addressed the incorporation of various finite element modeling and analysis functions into a database system that could be implemented by the USAF to facilitate their FEA efforts. However, through the direction of the Program Monitor, it was determined the priority was first to establish the need for a centralized FEM database and if the establishment of such a centralized system was cost-justified.

The major objective of this Phase I effort was to determine if it is feasible to develop and implement a centralized database system for finite element models of United State Air Force (USAF) aircraft structures. The second major objective was to develop a preliminary design concept and formulate an implementation methodology for the centralized FEM system.

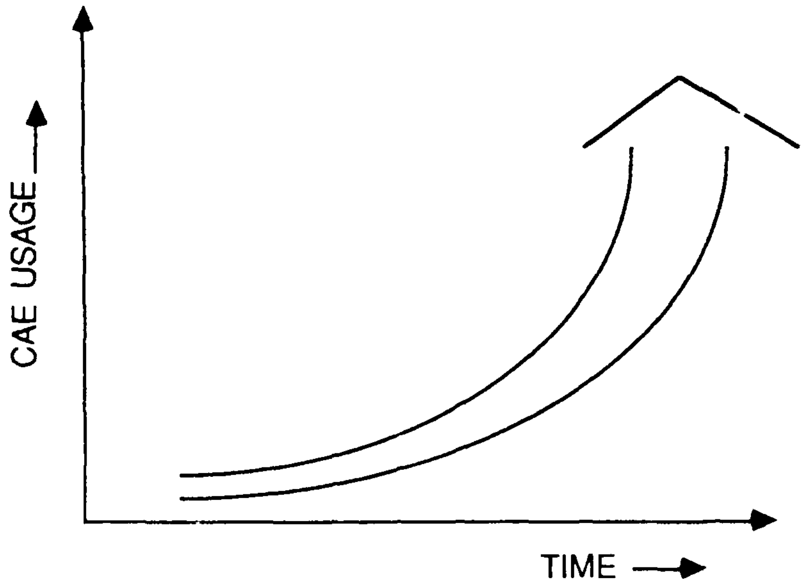


Figure 3.1 Trend in CAE

The approach was to determine the USAF methodology used to acquire FEM and the need for development of Air Force FEM delivery standards (as a contract deliverable). Acquisition of this background information was essential to the objective of the Phase I program.

In order to determine if a centralized database system is feasible there are several critical issues that have been addressed: (1) Is there enough current or potential use of finite element models throughout the USAF?, (2) What are the advantages and shortcomings of the present system and how can it be improved?, and (3) What are the benefits and costs of a centralized system and can it be implemented in efficient and cost effective manner?

A survey was designed by PDA Engineering to address these critical issues. The survey was divided into five sections: (1) Technical Background, (2) Finite Element Modeling Logistics, (3) Finite Element Modeling Tools, (4) Data Transfer, and (5) Centralized Database System.

The purpose of the Technical Background section was to familiarize PDA personnel with the background of the individual who was supplying the information. It was believed the duties and responsibilities of each organization would influence their finite element model and analysis applications.

The Finite Element Modeling Logistics section was included to help PDA understand the present methods which are used by the USAF to acquire finite element models and the difficulties involved with such efforts. This section also attempted to gather quantitative estimates of

manpower and monetary expenditures for FEM related tasks such as manpower spent to obtain FEM and model costs. These statistics were used to estimate extent of use of finite element models throughout the USAF and the cost of tasks in the present system which may be reduced and/or eliminated by a centralized database system.

The Finite Element Modeling Tools section was used to identify the various software packages and hardware used throughout the USAF. The data from this section was used to determine if recommendations could be suggested for improvements to the current approaches employed, and to propose a preliminary design of the centralized database system. It would be to the Air Force's advantage if the tools being used presently could be retained in the centralized database system mainly for economic reasons. Individuals would not have to be retrained on different software or hardware.

The objective of the Data Transfer section was to identify key features which are essential to data transfer and problems involved in transferring data from one source to another with respect to USAF applications. It served to identify the format most often used in data transfer. This information is needed to understand the problems of transfer of data between different machines in the event that different machines were used for pre- and post-processing and analysis.

The last section, Centralized Data Base System was used to determine if there is an interest among the potential users in a centralized system and, if so, what types of database features would be most beneficial. It also sought to explore the reasons against a centralized database system and the problems with implementation of such a system.

A general discussion section for other topics pertinent to finite element models use in the USAF, not covered by previous sections, was provided at the end of the survey. (A copy of the survey can be found in Appendix A.)

There were ten organizations and thirteen key individuals selected and identified by the Program Monitor to be sources of information. A copy of the survey was distributed to each of the key individuals. There were three individuals from AFWAL/FIBRA (the program-directing organization) which participated in the survey. The other organizations were spread throughout the Air Force in both the Air Force Systems Command and Air Force Logistics Command. There were five Air Logistic Centers that were involved: (1) Ogden Air Logistic Center at Hill AFB (OO-ALC; two groups, MMARA and MMSRA), (2) Oklahoma Air Logistic Center at Tinker AFB (OC-ALC), (3) San Antonio Air Logistic Center at Kelly AFB (SA-ALC), (4) Sacramento Air Logistic Center at McClellan AFB (SM-ALC), (5) Warner Robins Air Logistics Center at Robins AFB (WR-ALC). In addition to AFWAL/FIBRA, four other AFSC organizations were also selected: (1) 3246th Test Wing at Eglin AFB, (2) 4950th Test Wing at Wright-Patterson AFB, (3) 6520th Test Group at Edwards AFB, and (4) Aeronautical Systems Division at Wright-Patterson AFB.

It is to be noted that these organizations, according to the Program Monitor, do not represent all AF organizations using aircraft FEM; they were suggested as being representative. Equally important, they ranged from the very experienced in the use of FEA methods (e.g., AFWAL/FIBRA, WR-ALC) to the relatively inexperienced.

After the completed surveys were returned to PDA, a follow-up telephone interview was conducted with each of the respondents. Some form of response was received from all organizations except the 3246th Test Wing. Nine out of the ten organizations or 12 out of 13 people answered the surveys. Oklahoma ALC provided their information via telephone conversation only. Several groups including the 6520th Test Group, OO-ALC/MMSRA, and Oklahoma ALC had, as previously noted, only limited experience with finite element modeling and analysis.

The study participants have a broad spectrum of responsibilities, applications for finite element analysis, and levels of experience with finite element techniques. Their duties include flight testing, repair and maintenance of a variety of aircraft systems, damage tolerance assessment, assurance of structural integrity of modifications to aircraft, determination of nuclear effects, and maintenance and development of analytical software. The individuals surveyed had varying degrees of technical experience ranging from 1 year of aerospace structural engineering, 5 years of structural analysis, 15 to 20 years of aircraft testing, to over 20 years of research and development in structures.

The statistics compiled were averaged over the number of organizations polled so that the results would not be biased towards AFWAL/FIBRA. Not all the questions were answered by all respondents. In these cases, the statistics were averaged over the number of organizations which answered the question. The statistics were used to determine trends, to identify commonalities between organizations, and to derive estimates for costs.

There are approximately 45 people in the ten groups which responded to this survey who use finite element analysis. It was indicated by these groups at least another 20 people in adjacent organizations employed FEMs for aircraft studies. Dr. Venkayya estimates that there are a 100 or more individuals using FEM for related studies at Wright-Patterson. Given this information, and making allowances for organizations not surveyed, it would appear that there are on the order of 200 people in USAF employing FEM for aircraft applications. The structural analysts surveyed spent the majority of their time doing finite element modeling and analysis. The senior analysts spent some time doing their own modeling and analysis as well as consulting with others. Other senior level people supported finite element analysis activities in some capacity or did research and development on finite element tools.

Given the magnitude of FEA activities among the USAF aircraft contractors, this appears to be a relatively small number of personnel involved in similar activities. On one hand, this raises a concern as to if cost-benefit arguements exist for a centralized FEM system given the relatively few number of individuals involved. Conversely, given the magnitude of the responsibilities incurred by these individuals, a qualitative arguement is self-evident that their efficiency must be maximized to allow their responsibilities to be effectively carried out, which would be one benefit of the centralized FEM system.

After the survey was completed and the results analyzed, a methodology was formulated to provide a basis for cost-benefit assessments of the proposed centralized data base system. The Phase I program concluded by formulating a preliminary design for a centralized system.

5.0 SURVEY RESULTS: PRESENT FEM SYSTEM

The level of effort in current USAF FEM activities are first summarized. Several issues in the present system will then be addressed: the present method of obtaining and using finite element models; finite element model and analysis tasks; finite element tools; archiving procedures of FEM once obtained and used; FEM and its impact on testing; and the costs involved with the present system which may be reduced or eliminated.

5.1 Current Level of Effort in FEM Activities

There is an average requirement of 10 finite element models per year per person required by the individuals in eight of the organizations. Figure 5-1 shows the individual group estimates of FEM required per year per person. By extrapolating the data of 10 models/yr/person to the 45 people in the survey-groups using FEM, it appears that these groups alone need 450 or more finite element models per year. The levels of complexity of the models range from test models which may be a few hundred degrees of freedom (dof) to large internal models, 60,000 dof.

One individual estimated that the cost of a fully burdened manyear would be about $ 100K. This figure is used throughout this report as a basis for cost estimates. Survey results show that individuals spent more than 50% of their time involved in FEM and FEM related tasks. An estimate for the labor costs of FEM related work for 45 people would be $2.25 million per year. If this statistic is extrapolated to the estimated 200 persons previously derived then FEM-related labor costs are on the order of $10 million annually.

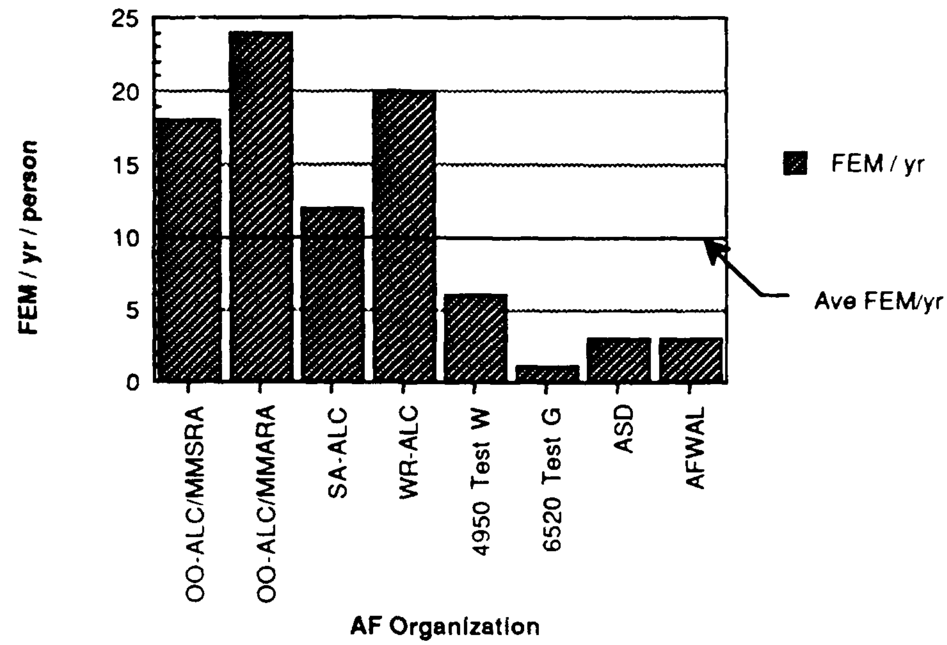


Figure 5-1. Number Of FEM Required By Surveyed Air Force Organizations

The Air Force also has considerable hardware and software resources committed to finite element analysis. Each organization has access to at least one mini-computer. For example, the ALCs usually have at least one dedicated mini-computer such as the VAX 11/780 or 11/785. Ogden ALC has two VAX 11/785 clustered together which is shared between two groups. Graphics devices and other peripherals are also available. They usually have some commercially leased software codes for both pre- and post-processing and analysis along with their own "in-house" developed codes.*

It is clear from this limited sampling of Air Force organizations that the Air Force has already invested a sizeable amount (millions of dollars) in both hardware, software and manpower resources. This investment is anticipated to increase substantially in the near term.

5.2 Present Method of Acquiring Finite Element Models

The typical mode of operation for acquiring finite element models in the present system was addressed by the survey. Although it was apparent from the survey response that there is no

*The U.S. Navy is preparing a major CAD/CAE/CAM procurement for five commands which originally called for the acquisition of 40,000 engineering workstations[2]. In a sense, this procurement constitutes the next generation of CAD/CAE/CAM technology. Extrapolated to the USAF, a similar approach would represent over an order of magnitude increase in computational capability available for CAE activities.

organized method for obtaining FEMs, there are some fundamental differences in the approaches used by the ALCs and the other organizations.

As stated earlier, there is an average yearly requirement for ten finite element models in the organizations surveyed. The average requirement for the Air Logistic Centers (ALC) is higher at 18 models per year. A possible reason for the higher estimate may be due to the need for detailed models. The ALCs' primary function is to provide "in-service" structural support (repair and maintenance) for their assigned aircraft system(s). Their duties include determining the causes of failures, recommending modifications, defining inspection intervals, and determining the effects of mission changes. They can also be involved in modifications to existing aircraft such as extending noses of C-135s or adding pylons on B-52Gs.

The typical flow for finite element model requirement and acquisition in the ALC can be characterized by Figure 5-2. Once the need for a finite element model is identified there are several sequences of events which might occur. The dashed lines in Figure 5-2 indicate possible paths. Personnel at the ALCs do not spend time trying to locate FEMs within the Air Force and then acquiring the models for their use. Often an applicable model maybe "on-line" on their computer.

For example, at Ogden ALC the large contractor-built models for the F-4 and F-16 are "on-line" along with other models that they have built. They must decide if an applicable model is available for their use. The reasons for concluding that an applicable FEM does not exist may be: (1) most often lack of data, (2) inability to locate model in a reasonable time, (3) cost or (4) need to generate models for a specific application. If an FEM is not readily available, then several alternatives are possible depending on the circumstances: build the models themselves or purchase the model from the contractor. They usually build detailed models from drawings. In Warner-Robins ALC's case, they often work with both drawings and the actual part. The ALCs tend to build their FEM more often than not because of their need for a specific application.

A typical model can be built within 0.6 to 2.5 manweeks with an average of about 1.4 manweeks. These models are fairly simple geometries, e.g, simple curvature and uniform thicknesses. A more complex model could take between 4 to 6 manweeks to build. An example of a typical model is a bulkhead model built by Ogden ALC in 24 manhours. It has about 1300 elements and took 4.5 CPU hours of VAX 11/785 time to run. There were three versions of this model analyzed. The first model was used to calculate the stress levels at the estimated failure loads. The next two iterations were used to examine the stress levels in the structure when a crack existed and to determine if the proposed repair was adequate. Geometry information is usually

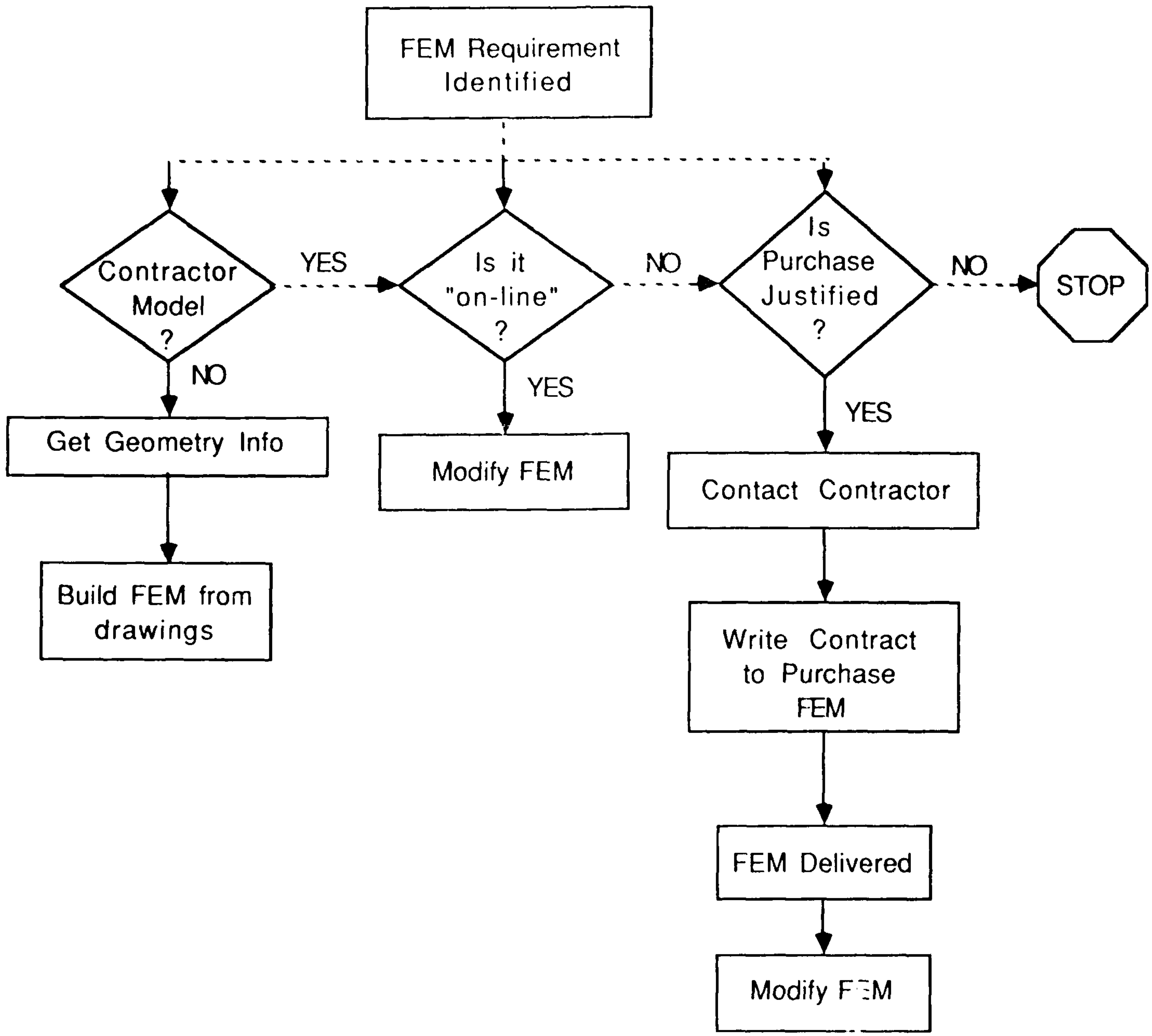


Figure 5-2. Air Logistic Centers' Typical Mode Of Operation

readily available for detailed FEM from the System Program Office (SPO). Often these drawings have been reduced and stored on micro-fiche and may not be of the best quality and dimensions must be scaled from drawings. It is not unusual for drawing requests from the SPO to take about two weeks.

The larger models such as internal loads models (about 60,000 dofs) are purchased from contractors. There are many facets involved in purchasing models from contractors including writing contract specifications, negotiations, documentation, and schedules. For example, in the case where F-111 models are being purchased from General Dynamics, the procurement cycle is scheduled to take 27 months and at this writing, models are being delivered (19 months after beginning of effort).

Although these models are costly and have long delivery times, ALCs obtain "validated" models. Validated models are ones that have been correlated with test results. There are several reason for this approach: (1) economics, (2) to take advantage of the finite element "know how" of the engineers in industry, and (3) to take advantage of the time invested in developing these models. These FEMs are used to simulate in-service problems of corrosion or cracking and to assess compatibility of structural components, e.g. they will utilize geometry information from an internal loads model and redefine the mesh for their application. ALCs have a need to analyze major components such as wings to validate load data which will be used for subcomponent evaluation (i.e., results of major component models are use as boundary conditions for a substructure).

AFSC personnel have a need for finite element models about 4 times a year. Their typical finite element model requirement and acquisition flow can be characterized by Figure 5-3. Unlike ALC personnel they tended to search for appropriate FEMs. Once a need for a FEM is identified, there are several possible paths, as indicated by the dashed lines in Figure 5-3, which could be followed to determine the availability of applicable FEM. Often it was assumed that a model didn't exist. If an individual suspected that a model existed within the Air Force then an average of 39 hours was spent to track the model down. However, they had no organized method for searching and obtaining finite element models. Usually it was by chance or coincidence that a model's existence was determined. The reason given most often in deciding against an applicable model's existence was the lack of data and the inability to locate models in a reasonable time. In ASD's case, if they found out about a model that might have potential use they usually tried to obtain it for possible future use. ASD is interested in internal loads models and flutter models. Even after a group had obtained a model they had varying degrees of success using the model. ASD spent a manyear of labor trying to input and verify a model it obtained from WR-ALC before they determined that the model was not usable. The details of this effort are described in Section 5.5.1. On a positive note, there was also a report of a successful use of a flutter model by the 4950th Test Wing which took about 5 manweeks to implement properly and understand (see Section 5.5.1).

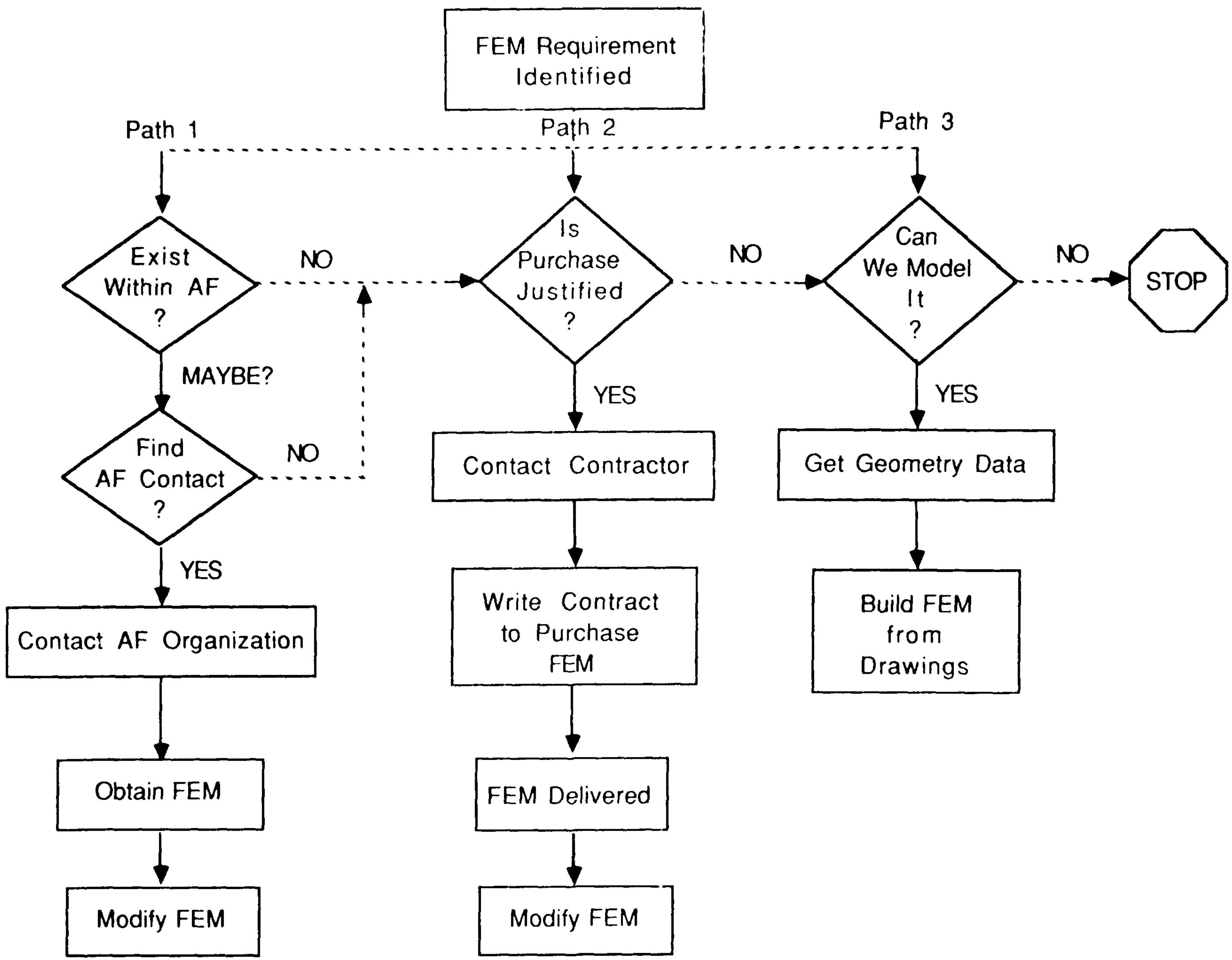


Figure 5-3. AFSC Organizations' Typical Mode Of Operation

Other possible paths to obtaining FEM were purchasing the models from contractors or building the models themselves. Purchasing models from contractors presented the same problem for AFSC personnel as for ALC personnel. One individual said that "if they got a model within a year it was considered good turn around time." Models obtained from contractors have been used for geometry information. They purchased "validated" models for the same reasons as ALCs. Geometry information for the models which they built was available from SPOs via drawings. The delivery time for drawings were about two weeks. Typically the models built from drawings required between three to eight manweeks of labor. In the cases when Class II modifications were done, drawings were often immediately available. At the 4950th Test Wing, the geometric information can be transferred from their CAD/CAM system to FEM data within an integrated software package. This may save an estimated 25% of labor for models which take on the order of one week to be built from drawings.

The average delivery time for a model was 3.3 months excluding those organizations which had models "on-line". This time included delivery time for models for which there were no additional charges and those which were acquired from other AF organizations. In the cases where models were bought from contractors, delivery time ranged from 8 months to 1 year.

5.3 Finite Element Model Applications

5.3.1 Finite Element Tasks

Once the models were received at their job sites there were various tasks to be completed in order to make the model useful for their application or to extract the appropriate data from the models. The survey participants were asked to estimate the percentage of time spent on each of the finite element model related tasks: (1) model conversion into usable format for pre-processor, (2) modify geometry and/or mesh, (3) change loads, boundary conditions, and/or material properties, (4) run analysis and study results, (5) no changes (run "as is" on their software), and (6) other. Figure 5-4 shows the average breakdown of finite element tasks among the organizations. About thirty two percent of the time was spent running analysis and studying its results, 23.6% changing loads, boundary conditions, and/or material properties, 22.2% modifying geometry and mesh, and 22.1% converting model into usable format.

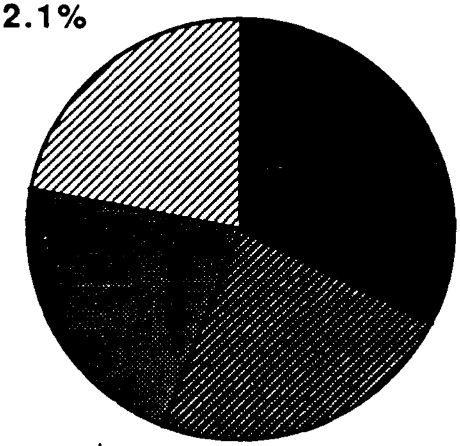


Figure 5-4. Task Time Distribution for Existing Finite Element Models

PDA believes that reasons for some of these tasks, such as format conversion and load modification, is the lack of standards for finite element information. FEM information are often given to an interested AF organization in tabular computer printouts rather than tape. Often loads are not given to the engineer in a run deck format which would facilitate the use of the model. Instead, in one case, the engineer was given aerodynamic coefficients or in another a flight envelope was given to the engineer. In still another case, the loads were not given at all and the engineer spent some time trying to simulate the expected results from a completed analysis. Model format conversions often take considerable time especially if a different code is going to be used than the model was built for. First the engineer must try to determined what was done by the original modeler with the available documentation (which may be none) and then the appropriate corresponding element types must be determined.

5.3.2 Finite Element Tools

The assessment of the tools being employed in the current system will determine some of the functions of a centralized data base system and potential compatibility problems of such a system. All of the organizations have or will have a commercially supported pre- and post-processor. Six of the ten (60%)groups have PDA's PATRAN while five of ten (50%)have one of SDRC's packages, either GEOMOD, SUPERTAB, or IDEAS. In addition to these software packages, five of the ten (50%) groups have other software packages such as CADS, GIFTS, GRASP, and GRAFEM. SM-ALC currently has GRASP but will be replacing it with PATRAN.

GRAFEM is part of a CAD/CAM and finite element analysis package which is available to 4950th Test Wing personnel. They also have SUPERTAB. In the past, they have had some compatibility problems when trying to convert their models into NASTRAN models. In order to alleviate this problem, they will be getting PATRAN.

The organizations have a wide variety of analysis codes available to them. Sixty percent have COSMIC/NASTRAN, 80% have MSC/NASTRAN, and 90% have other codes which include GIFTS, GRAFEM analysis module, SUPERTAB, IDEAS (MODEL SOLUTION), PATRAN Stress Module, and ASTROS.

When pre-processors are used, reformatting of data into a format that is usable by the analysis codes is required. In the case of SUPERTAB, these are internal routines which are transparent to the user and may appear as menu selections. PATRAN also has interfaces which convert formats to a variety of analysis codes such as COSMIC/NASTRAN and MSC/NATRAN. Currently the Air Force uses translators which convert PATRAN data to COSMIC or MSC, SUPERTAB to MSC/NASTRAN, CADS to COSMIC/NASTRAN, and GIFTS to NASTRAN.

The hardware categories were divided into computer and graphics devices. All groups have access to either a VAX or a CYBER. Ninety percent of the groups have Digital Equipment's VAXs which range from the 11/780 to the 8600. OO-ALC has two VAX 11/785 clustered and will soon be upgrading to an 8800. Forty percent have access to a CYBER machine. ASD will be switching from a CYBER to a VAX in 1988 (they have been included in the 90% VAX statistic). Two of the organizations, 4950th Test Wing and AFWAL/FIBRA, also have or will have access to a CRAY. The 6520th Test Group at Edwards has a HP9000 and access to a CYBER. In most cases, the same machine is used for building and analyzing the model. In the cases where different machines are used, information transfer is usually done by magnetic tape or through a network. For magnetic tape transfers, the estimated labor ranged from 2 to 16 manhours with an elapsed time of about 48 hours. For network transfers, the estimated labor was 0.5 manhours with an elapsed time ranging form 0.5 to 48 hours.

The most popular graphics device was Tektronix. Eight groups had Tektronix terminals ranging from 4014 to 4129. Two groups had an Evans and Sutherland (E &S) terminal. AFWAL had both E &S and Tektronix. Other terminals used included VAX II work station, HP9000, and Applicon Graphics CAD/CAM Bravo 3.

5.3.3 Impact of Validated Models on Testing

Whenever any modification is made to an aircraft, its structural integrity must be verified by either one of two avenues: analysis or testing. Hand calculations, in which simplifying assumptions are made, can be used to verify the structural integrity of a modification provided that

a specified allowable margin of safety is met. Finite element analysis can provide significantly refined estimates over hand calculations. Testing to verify structural soundness can be done by either static or flight testing. In static testing, a portion of the aircraft is supported by a fixture and instrumented. then it is subjected to one or more loading conditions. Flight testing requires that the aircraft be instrumented with strain gages, telemetry devices, etc., flown through various maneuvers, and then results reduced.

In years past when there were limited analytical tools available, structural integrity of an aircraft was estimated by hand calculations and extensive testing. With the advent of finite element techniques, some types of structural testing may be reduced. In order to reduce testing costs, validated finite element models must be available to the analyst and designer. It is important to note that validated models refer to finite element models that have demonstrated results which have been correlated to tests. Finite element models are simulations of the actual physical characteristics of a structure and there are many simulation variables (such as boundary conditions, element selection, material properties) available to the analysts. The importance of verifying that the model is simulating the actual structure by comparing analytical results to test results is illustrated in the following example.

A linear static stress analysis was done of a T-37 empennage. This was a symmetry model which contained 1200 nodes and about 3800 dof. The structure was modeled with plate elements. The results of the FEA were considerably lower than the stresses (stress levels necessary to exceed the threshhold for cracking) in the actual part for the same loading conditions.

The analysis was predicting a wing tip deflection on the order of 0.5 in. while in the actual structure the deflection was about 6.0 in. A closer examination of the part showed that there was buckling in the upper skin (non-linear effects) which meant that there was little or no stiffness being provided by the upper skin. Once this modification (membrane were changed to shear panel so that these elements were not carrying any in-plane tension or compression) was made to the model, the tip deflection predicted by the model was about 5 in. The smaller deflection in the analysis was suspected to exist because of the difference in boundary conditions. The model had a stiffer restraint than the test. This model, modification, analyses, and results correlation cost between $ 70K to 90K. This includes time to build it, realize there was a problem and modify the model. This example shows that in order for FEA to be useful the confidence in the model must first be established. However, once it is established by correlating results with test data this model may be used in reducing future test costs. With the use of validated models, the analyst has confidence that the model is simulating what is going on in the structure. Some of the testing requirements can be eliminated. Often testing results exist for an aircraft from the acquisition phase and no additional test are required to validate FEM.

Sixty percent of the survey participants are or have been involved in testing of modifications to the aircraft.* It was estimated by the individuals involved in testing that 12% of the time modifications were tested instead of analyzed because of lack of finite element information. They also felt that finite element analysis could be used to aid in testing 54% of the time. Admittedly there will always be some types of testing which can not be reduced or replaced by analysis regardless of if the finite element information is available, however in the cases when testing costs can be reduced there should be a substantial cost savings. Estimates for potential cost savings in testing due to the use of validated models ranged from 25 to 50%. The turn around time for finite element testing can often be considerably quicker that for the testing.

5.4 Archiving Finite Element Models

There are no formal procedures for documenting a finite element model once they are used by AF organizations. Each organization usually documents the models in report format and the contents of the report are determined by the individuals involved in the finite element analysis. In the case of the 4950th Test Wing, they have some informal guidelines as to what type of information may be included in their internal documentation. These are: (1) figures of the model, (2) node and element identification, (3) in some instances, a copy of stress results deck, (4) copy of input deck, (5) summary of the results, (6) sketch of cross-sections and how the properties were calculated, and (7) any unusual features such as the rationale used to pick between a rod and shear panel or beam elements.

In some groups, models are "backed up" and stored on magnetic tape and in others the models are kept "on-line". At SM-ALC, after the models have been used, they are stored on tape. The models are normally stored as analysis run decks. A log is kept of the models which includes what analysis code was used and the title of the model. They often don't have the resources necessary to document their models adequately. At the 6520th Test Group at Edwards AFB, the models are usually kept until the testing of the modification was done. This may be a year or so. The results of the analysis are filed along with the appropriate report, but no tapes are written. It was felt that there will be no future use of the FEM used to assess Class II modifications since they are unique.

5.5 Costs and Liabilities

Cost estimation of the present USAF system of acquiring and using finite element models of aircraft structures to support USAF analytical requirements will be estimated in the following

*Four of the ten participating organizations supplied cost information for their testing activities. The sum testing costs for these four organizations exceeds $20M. This datapoint can be used to extrapolate to the total Air Force expenditure for aircraft testing. The Air Forces annual expenditure is probably in excess of $100M for aircraft testing.

section. In order to estimate the cost of the present system, one would have to examine in detail all the manpower and computer resources which are involved in every aspect of finite element modeling and analysis activities throughout the entire USAF. This would be a formidable task which would probably not prove to be very cost effective. Instead of doing this, the information gathered from the key personnel in ten organizations throughout the USAF was used to estimate costs of the present system. It is obvious from the results of this study that there is no standard method of acquiring finite element models and that FEM are not usually obtained as contract items when a system is bought by the Air Force. The costs of obtaining and implementing models in an ad-hoc fashion will be illustrated with examples.

The cost examples will illustrate several classes of problems which could be reduced or eliminated by the implementation of a well designed centralized database system and/or the implementation of AF FEM standards for deliverables. Quantitative examples of the shortcomings of the present system can be divided into the following categories: (1) model acquisition, (2) duplication of effort in data transfer, and (3) model conversion. The first set of examples are those in which Air Force organizations has purchased finite element models and the corresponding documentation from contractors after the system has been delivered. Several cases of inefficient finite element data transfer from one organization will be used to illustrate the duplication of effort problem in the current system. Model conversion costs and difficulties will be addressed in the last set of examples. Other cost issues such as delivery time and interpretation of insufficiently documented models which are harder to quantify will be discussed qualitatively.

5.5.1 Model Acquisition

At least eight of the ten (80%) organizations have obtained models from contractors at sometime. Five out the eight (62 %) have purchased finite element models along with documentation from various contractors including General Dynamics and McDonnell Douglas. The cost of these models range from $ 50K to $ 200K. These numbers are estimates of the price paid to the contractors. They do not include the labor which was necessary to write the specifications for the finite element model and documentation as delivered contract items. It was estimated that more than half of the cost of these models was for documentation. Some models could have been obtained without charge if documentation was not required. However this is usually not a viable alternative due to the complexity of all the models purchased. Models without any form of documentation would be next to useless since it would take countless labor hours to decipher what the original modelers were trying to simulate.These models were delivered in analysis run deck format (primarily MSC/NASTRAN) format usually on magnetic tape. Another important cost consideration of obtaining models in this fashion which is harder to quantify is the impact on scheduling due to the long delivery times involved.

F-16 Models at Ogden Air Logistic Center - $ 125K

Personnel at Hill AFB (OO-ALC) have bought several large F-16 finite element models from General Dynamics. These models had an estimated cost of $ 125K. These models are currently "on-line" on their computer for use by Ogden Air Logistic Center personnel. The format for these models was analysis code run decks. The largest model purchased in this arrangement was a wing model which includes over 8300 elements (both plate and beam) and 15,000 degrees of freedom. It was estimated by OO-ALC personnel that it would have taken about 3 manmonths of labor to construct this model. One of the smaller models was a horizontal stabilizer which included 1334 elements and about 2300 degrees of freedom. Manpower necessary to build this model was estimated at approximately 3 manweeks. These models have not been used at this writing so consequently a judgement cannot be made on the adequacy of the documentation provided with these models.

F-111 Models at Sacramento Air Logistic Center - $ 185K

The Sacramento Air Logistic Center (SM-ALC) at McClellan AFB is in the process of obtaining finite element models for the F-111 aircraft. In this case, seven models and documentation were purchased from General Dynamics at a total cost of $ 185K. The F-111 finite element model transfer activity was scheduled to span 27 months from June 1986 to September 1988 (reference Force Management Technology Application Program Management at Sacramento Air Logistics Center, 18 Feb 1987). The delivery time for these models was about 8 months. The largest model bought was that of the entire F-111 aircraft with an estimated 60,000 degrees of freedom, at a price of $ 63K. The sizes of the rest of the models were not available. Other structural components finite element models included were horizontal tail pivot shaft ($ 24K, 6.5 hrs CPU on CYBER 72 for a linear static analysis), wing pivot fitting ($ 17K), wing pivot stiffener #2 runout ($ 15K), wing pivot field flow holes 13 and 14 ($ 15K), TP2 inlet ($ 22K), and an unidentified model costing $ 29K. The documentation accompanying these models are supposed to be the equivalent of a user's manual which explain how to use these models and the physics they simulated. At this writing, two of the seven models had been delivered and the documentation has not been reviewed in any detail to determine if it is sufficient.

C-130, C-141 Models at Warner Robins Air Logistics Center - $ 100K to 200K

Warner Robins Air Logistics Center has purchased finite element models for the C-130 and the C-141 from Lockheed under contract. The cost for these models are estimated to be between $ 100K and $ 200K. Documentation was provided, but information on loads and multi-point constraints and other not commonly used cards was inadequate. Engineers often had to study the drawing and the part and consult with others in order to understand what had been modeled. Load information was not supplied in analysis code run deck format but a load envelope was supplied

instead. A description of the load application was not sufficient and it took several attempts by the engineers to apply the loads which gave t'vo reported results. (Part of the reason that these models were purchased long after these systems were acquired is because finite element technology was not available in the 1950's and 1960's when these aircraft were built. In fact, the documentation reflects the early finite element technology when interactive pre-processors were not available and thus a considerable amount of documentation entails different views of the model which are not very valuable given the advances in interactive graphics.)

F-15 Model at Warner-Robins Air Logistic Center - $ 50K to $ 100K

WR-ALC has also ordered a model of the F-15. It is assumed that this model will cost on the same order as those in the following example at ASD.

F-15 and F-16 Models at ASD, Wright-Patterson AFB - $ 50K to $ 100K

Two versions each of F-15 (F-15B, F-15E) and F-16 (F-16A/B, F-16C/D) models have been purchased by ASD at Wright-Patterson AFB and range in price between $ 50K and $ 100K. Documentation was provided with these models. These models are internal loads models of the entire aircraft which are estimated to have about 60,000 degrees of freedom. The estimated delivery time for these models if bought on contract is 1 year. At one point, ASD also inquired about the cost involved in building an internal loads model from drawings. The first order estimate to build this type of model was $ 1 million.

Model Acquisition from other AF organizations - $ 15.6K

In some instances, when AFSC organizations suspected that a finite element model existed within the AF, they spent an average of 39 hours searching for the model. Finite element models were available for their use about 13 % of the time and these organizations had an average need for 64 models per year. A conservative estimate for the time used to search for models, by the four AFSC organizations which responded to the survey, on a yearly basis is about 8 manweeks. If it is assumed that a fully burdened manyear costs $ 100K then 8 manweeks cost the Air Force about $15.6K.

5.5.2 Duplication of Effort

In the present system there is often times a duplication of effort in various tasks. Some of these inefficiencies could be reduced and possibly eliminated if a centralized system is implemented. Additionally, some FEM were delivered as tabular listings and AF personnel had to transfer the data manually. The following example is one in which immense manpower was used to recreate a model that had already been built elsewhere and had been used at WR-ALC, but it was

not available in a form that could have been easily used at ASD at Wright-Patterson. Throughout this study there have been other incidences of duplication of effort identified but the cost associated with these are not easily estimated. The cost estimates for examples described below are estimates based on a manyear costing $ 100K and the respondent's estimate as to the labor involved in some of the FEM tasks. Some discussion addressing how these may be reduced will be forthcoming.

Warner Robins' F-15 Model given to ASD at Wright-Patterson - $ 100K

This incident is probably an extreme case of duplication of effort. This ineffective use of resources could have eliminated if a centralized database system had been implemented. ASD at Wright-Patterson AFB discovered that there was a version of F-15 at Warner Robins AFB. The model was given to them in the form of a reduced copied computer listing. This model had about 20,000 nodes and 60,000 degrees of freedom. The model was input to their computer system by keyboard. It took an estimated 6 manmonths of labor to enter the data and an additional 6 manmonths to check the data input. When the model was brought up on the graphics screen it was determined to be unusable. A requisition was then submitted to the SPO to purchase the model from the contractor. If it is assumed that a fully burdened manyear costs $ 100K. Then the effort of entering and checking this model can be estimated to cost $ 100K

C-135 Model at 4950th Test Wing at Wright-Patterson AFB - $ 9.6K

In this case, the 4950th Test Wing used the information in a report of a flutter model (stick model) of C-135. This model was on the order of 100 nodes.The reason the information of this model was transferred in this way was because that model was at least 5 years old. It took about 3 to 5 days to put the data into the computer and approximately one manmonth to verify the model and the analysis results (part of the time included in the labor estimate includes time for a learning curve about flutter models). Some of the labor time included learning the updated system, finding errors and program changes (such as the solution number of the analysis code had changed and tracking down errors reading a bad copy of the analysis input deck). The report provided some narrative as to what the model was used for i.e, model application and purpose of the analysis. Figures of the model were also provided in the report. The Test Wing had a similar application and they needed to modify it slightly for some component that they were going to add to the wing. This information was taken from an internal research and development report. This was example of one of the better instances when they were able to use data generated by another AF organization. Assuming it cost $ 100K per manyear the labor, 5 manweeks, for this effort would cost $ 9.6K.

X-29 Flutter Model at Edwards

Although this example is not one that could have possibly been cured by a centralized database system, it is included to illustrate the potential application of FEM transfer outside the bounds of the Air Force. In this case, a flutter model of an X-29 which was used at NASA (originally obtained from Grumann) was brought to the Test Group along with the individual who had worked with the model. The model was input to the computer via keyboard and took considerable manpower, but no estimates were given. This is the first model of its kind to be used in this Test Group. It will be used as a learning exercise for flutter analysis as the personnel there become more familiar with finite element techniques in flutter analysis.

Insufficiently Documented Model at AFWAL

Adequate documentation of a FEM is crucial to reducing the amount of time spent trying to interpret what the original modeler did. Several individuals at AFWAL have received models without sufficient documentation. In one case, a model which had about 700 dof was received without any documentation except for the comment cards in the actual run deck. The dimensions of the structure was supposed to be changed and the analysis redone. Over the following six months, the model was worked on periodically, however, all the subtleties of the model are still not fully understood. In another case, an engineer received a model of an L-1011 wing with some documentation. The model was to be used to verify a new analytical tool. This model was originally built by Lockheed with their own version of NASTRAN (which is no longer used). It was also used by NASA for some optimization work. The documentation provided lacked the description of bulk data cards which are critical to the understanding of the model. Several efforts have been made over the course of a few months to obtain the needed data, but at the time this information was supplied to PDA, these efforts had not proven successful.

5.5.3 Model Format Conversion

Warner-Robins Air Logistic Center Model Conversion - $ 450K

Warner Robins Air Logistic Center recently had a large finite element model (about 20,000 to 30,000 degrees of freedom) converted from COSMIC/NASTRAN to MSC/NASTRAN. The cost for conversion was about $ 450K of which more than half was for documentation. There are many incompatibilities between the two codes which make a one-to-one conversion difficult. In this instance the differences included: (1) superelement capabilities used in MSC/NASTRAN do not exist in COSMIC/NASTRAN and (2) MPCs (multi-point constraints) in MSC/NASTRAN had to be replaced with ASET cards.

San Antonio Air Logistic Center Model Conversion Quote - $ 200K

San Antonio Air Logistic Center has also had the occasion to inquire about the cost to convert a T-38 full airframe model from MSC/NASTRAN to COSMIC/NASTRAN. A first order estimate of $ 200K was quoted to them. They have chosen to lease MSC/NASTRAN because of the cost savings. It costs them between $ 25K and $ 30K per year to lease MSC/NASTRAN.

ASD "In-house" Model Conversions - $ 11.5K

ASD personnel at Wright-Patterson AFB have also had the need to convert large internal loads models from MSC/NASTRAN to COSMIC/NASTRAN on at least two occasions. Often times in their organization the internal loads models (20,000 nodes; 60,000 degrees of freedom) are used as a database for geometry and other physical property information such as skin thicknesses. They could have had the contractor convert the models to COSMIC/NASTRAN but they would have lost some of the information for options which were not supported by COSMIC. For instance, the thickness information in MSC's tapered plate elements would have been lost. ASD decided to obtain the finite element models in MSC/NASTRAN run deck format and write their own software to convert the information at their site. The biggest problem they have in converting these decks is the incompatibility of element types between the two codes. About three weeks of labor was necessary to write the software for each conversion. This manpower estimate includes only the time involved in reformatting the data and does not necessarily mean that the converted data will be a valid MSC/NASTRAN run deck.

5.5.4 Liabilities

There are other costs in the present system that are not easily quantifiable that may be alleviated in a centralized database system. These include the effect of delivery times for models purchased from contractors and the availability of validated models to reduce testing of aircraft.

Delivery time is a cost of the present system that is hard to quantify because it is not known how the delay in obtaining the model will impact schedules and decision-making.

Flight testing costs can be on the order of $ 700K to $ 800K. This includes test pilot wages, instrumentation of the aircraft, test planning and reduction of data. An engineer estimated that a model which addresses the same concerns could be built in about one manyear ($ 100K / manyear). Assuming that this model can be validated with other already existing test data, and that the additional costs involved such as computer cost, validation and modification of the model are about triple the original model creation labor costs, the potential cost savings can be in the neighborhood of $ 300K to $ 400K. This is the potential cost savings for a single system. It is conceivable that savings throughout the Air Force for other systems could be on the same order.

In the above examples, a conservative estimate of the total monies paid to the contractors for FEMs is in excess of $ 760K. The cost of FEMs purchased from contractors is summarized in Table 5-1. This is a partial list of the monies spent by AF organizations. This does not include any labor hours required to specify and procure these models. It was estimated that half of the these costs were for documentation to support these models.

TABLE 5-1 COST OF MODELS PURCHASED FROM CONTRACTORS

Fem Description	AF Organization	Price Estimate $1,000
F-16 models	00-ALC	125
F-111 models	SM-ALC	185
C-130	WR-ALC	~100-200
C-141	WR-ALC	~100-200
F-15	WR-ALC	~50-100
F-15 (2 versions)	ASD	~50-100/ea
F-16 (2 versions)	ASD	~50-100/ea
TOTAL		**>$760**

If a specification were written to require that finite element models along with "standardized" documentation and stress reports were part of the deliverables of a system, a portion of these documentation costs could be saved. Although not all of these costs can be eliminated, it is believed that possibly at least : 0% maybe more can be saved. Even in the case where aircraft were built in an era when finite element technology did not exist, standardization of documentation and finite element models could help to substantially reduce costs. Contractual provision for documentation could also provide the analysis element with an incentive for careful self-checking. Documentation at the time the models are built should be less labor intensive than at some future time since the time necessary to achieve the modeling strategies should be minimized.

Other miscellaneous costs resulting from poor communication and control in a dispersed system are summarized in Table 5-2. These costs amount to about $587K. Potential cost savings by using validated FEM to reduce the extent of testing, in some cases, could result in the flight test savings on a single system of $300K to $400K. Given the number of aircraft systems supported, savings could easily exceed $1M.

These costs estimates are based on the information conveyed to PDA by the survey participants. These values reflect their best estimates, recollections, and typical modeling duties and tasks.

TABLE 5-2 PRESENT SYSTEM MISCELLANEOUS COSTS

Description	Labor (manweeks)	COST	estimated$* ($1,000)
F-15 model ASD got from WR-ALC	52	→	100.
WR-ALC FEM conversion from COSMIC/NASTRAN to MSC/NASTRAN			450.
Miscellaneous cost estimates			
-AFSC cost tracking FEM	~8	→	15.6
-ASD write software to reformat COSMIC to MSC (not model verification)	~6	→	11.5
-GD analysis (ea analysis)			>10.
Total			**>587**

* Labor cost estimates are based $100K/manyear

5.6 Conclusions

There is sufficient FEM use and resource commitments to consider a method for FEM information management. The lack of an organized method in the present system of obtaining and archiving FEM warrants consideration of a centralized function to control finite element information. In some instances, the application of FEA is in its infancy and as the knowledge of the utility of validated finite element models increases, the frequency of use and the population using finite element techniques will increase. The management of FEM information will become more critical as its use increases. Standardization of FEM data will be necessary for efficient processing of data in a centralized system. The need for some type of standardization in acquiring

finite element models is apparent as a result of the examples presented in the preceeding sections of the drawbacks and shortcomings of the present methods.

6.0 COST AND POTENTIAL BENEFITS OF A CENTRALIZED FEM SYSTEM

6.1 Cost of the Dispersed System

A precise evaluation of the worth of a centralized finite element model system is difficult to achieve. There exists a number of quantitatively immeasurable advantages to such a system. They are immeasurable in the sense that any quantitative evaluation could contain an order of magnitude error with no means of verification. The fact that the system does not presently exist adds another level of difficulty to the evaluation attempt.

The strategy adopted to solve this dilemma is to evaluate the system that does exist. PDA has attempted to determine the costs incurred by the Air Force in conducting FEM/FEA due strictly to the fact that the present system is dispersed. The logic being that a centralized system will reduce or eliminate these cost, ergo the value of the centralized system is established.

The approach is to estimate the cost of the following five factors as a function of the systems dispersion. The five factors are as follows:

1) Cost of acquiring models from contractors;
2) Cost of duplicated efforts;
3) Cost of non-availability of FEMs;
4) Education/Training costs of poorly documented models;
5) Search/Information Acquisition Costs

6.1.1 Cost of Acquiring Models From Contractors

The survey conducted by PDA indicated that contractors are willing, for the most part, to provide F. E. models to the requesting Air Force units. Documentation of these models is the dominant cost the contractor bills to the Air Force. Our survey demonstrated that these documentation costs can be substantial.

PDA's survey of ten Air Force units and forty-five finite element analysts determined that at least $760K could be identified as having been paid to contractors in the recent near-term to obtain documented finite element models. In addition to the original cost of developing these models, this cost does not include the costs incurred by the Air Force in establishing the need for the models, writing specifications for documentation, purchasing activities, auditing activities, and the cost of resolving the problems of transforming the delivered models into usable form (documented to be very expensive in some instances). PDA estimates the Air Force incurred costs, conservatively, of

over $2M to obtain FEM from contractors in this time period. In addition, PDA identified over $500K in miscellaneous costs associated with the present system, which probably represent less than 50% of these types of costs created by the present system. If one assumes that a centralized system would save about 50% of both types of costs, then this indicates an excessive cost of $1M to $2M per annum for the present system with the higher figure believed to be the most reasonable based on the documented recent activities.

A second approach was taken to verify this $2M estimate. Dataquest [1] documented that in 1986, MSC/NASTRAN, Swanson (ANSYS), PDA Engineering, and SDRC, combined, sold $74.4M of FEM/FEA software in North America. The aerospace industry comprises 20% of PDA's software customer base. Assuming this ratio is constant across the four companies, the aerospace industry purchased in 1986 about $15M of this software (20% of $74.4M), and this amount is increasing. It is a reasonable assumption that the amount of money spent by the aerospace industry in conducting FEM/FEA activities is probably an order of magnitude above what was spent on software (i.e. $150M annually). To be conservative, we will assume that only $15-30M was spent on FEM/FEA by this industry on aircraft analyses that are of interest to the Air Force with respect to this solicitation. The fact that our survey indicates that the Air Force annually spends about 10% of this amount (see the previous paragraph) to acquire industry-developed FEM would appear to be a realistic, consistent and, probably, conservative number.

6.1.2 Cost of Duplicated Efforts

PDA's survey indicated that little to no coordination of effort exists between Air Force units with regard to building FEMs. Thus some duplication of model creation effort can be reasonably assumed.

PDA's survey indicated that there are at least 200 engineers dedicating an average of 50% of their time on FEM/FEA for aircraft applications. Assuming a burdened man-year cost is approximately $100K, it can be concluded that $10M is spent on aircraft FEM/FEA by the Air Force each year for man-power only. In an FEM/FEA activity, approximately 75% of the effort is in modeling, or $7.5M (75% of $10M). Assuming 10% of this effort is duplication, and this appears conservative based on our survey indications, then approximately $750K is spent on unnecessary duplication of aircraft FEM, annually, by the AF.

6.1.3 Cost Of Non-Availability of FEMs

If information is not available to create an FEM to evaluate a technical question, then some type of ground test, a prototype test or flight test alternative must be used to resolve these issues. PDA's survey and experience shows that such a test program can easily cost approximately $1M. It is reasonable to assume that at least one such test is conducted annually because of lack of a

readily available FEM model. Therefore, a conservative estimate is that $1M annually is spent on test programs to obtain information that could be determined through FEM/FEA, savings that would accrue if a centralized system existed.

Note that our survey suggested by the respondees that approximately 12% of total testing costs could be saved if appropriate FEMs were available. This aspect was not elaborated upon in the original survey. Follow-on telephone conversations with some of the ALC's and Test Groups indicated that the annual Air Force budget associated with relevant testing activities is in excess of $100 million. This suggests that savings through more extensive use of FEMs, part of which would result from the existence of a centralized FEM system, would be on the order of $12 million. This makes the $1M estimate, previously stated, a very conservative number.

6.1.4 Cost Of Education/Training For Poorly Documented Models

PDA's survey discovered that a poorly documented FEM could and often does require many man-hours to put a model in usable condition.

5% of the engineers time engaged in FEM/FEA activities appears to be a conservative estimate of the time lost in this aspect of FEM utilization by Air Force Engineers. This cost is estimated at $500K (5% of $10M)

6.1.5 Search/Information Acquisition Cost

Since there is no central location from which to start a search for FEM model information, this activity can be quite time consuming. The survey indicated a disparity in approach to this problem in AF organizations involved with FEM. Overall, it appears a significant amount of time was spent on this type of activity. Again, about 5% of an engineer's time is a reasonable estimate for this activity. The cost incurred for this activity is also on the order of $500K (5% of $10M).

6.1.6 Total Costs Of A Dispersed System

Combining the costs for each criteria:

6.1.1	Acquiring Contractor's Models	~$2.0 M	
6.1.2	Duplication of Models	~$0.75M	
6.1.3	Non-Available F. E. Models	~$1.0 M	(potentially $10-$12M)
6.1.4	Educational/Training Costs	~$0.50M	
6.1.5	Search/Information Costs	~$0.5 M	
	TOTAL COST	~$5.0 M	

Thus the present dispersed system is costing at least $5.0M annually for inefficiencies that could be greatly reduced or eliminated by a centralized FEM system. It should be emphasized that this $5.0M cost is due strictly to the fact that the system has no centralized control capability, or, put in a different perspective, a centralized system has the potential to save at least $5M in costs annually. Given the conservatism that was employed in making these estimates, the potential is believed to be much greater.

This study should also be judged in context of the growing use of MCAE. Figure 3-1, Trends in CAE, is reproduced as Figure 6-1, with the time of PDA's survey superimposed. The point of this illustration is to convey that the value of a centralized FEM system should increase in time as the utilization of MCAE technologies increases.

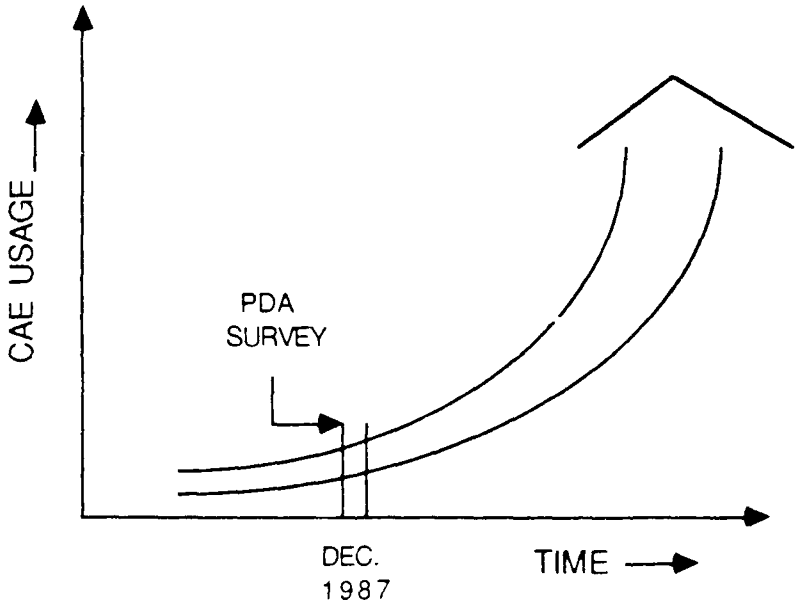


Figure 6-1. Time Perspective of PDA FEM Survey

6.2 Potential Tangible Benefits Of A Centralized System

A centralized FEM system can be implemented in various ways, offering different capabilities. The following paragraphs enumerate the capabilities that can be incorporated and the advantages associated with them.

6.2.1 A Standard For Format and Documentation For All Models

Defining a standard for the data format as well as the level of documentation has a number of advantages. The FEM will always be documented to a specified level at a minimum. Further, the model will always be delivered to the end-user in an edit-ready format which is totally familiar to the user. These two facts will drastically reduce the engineer's learning time on familiarizing himself with the FEM. The "edit-ready" format or state implies the user will receive the model in a condition that he can quickly install it on his system and begin to work with the model. The standard format of the data will be critical to facilitating the handling and transfer of a FEM throughout the centralized system.

6.2.2 A Series Of Translators For Data Preparation

The "edit-ready" format implies a FEM can be quickly installed on a system regardless of the hardware and software of the system from which it originated or the hardware and software of the destination system. This capability is accomplished through a series of "translators". A translator is a software utility used to reformat data and prepare it for input to a specified hardware and software system configuration. The centralized system will require a series of translators to serve the variety of computer equipment available throughout the Air Force. These translators will have to process the FEM coming in from the contractors as well as the models going out to Air Force organizations. They are a critical link to insure smooth communication throughout the centralized system. The effectiveness of these translators will govern the level of costs incurred by Air Force units preparing models obtained from the centralized system for use.

6.2.3 An "Automated" Model Documentation Capability

It is possible to develop software that can review FEM and document 70% of the models pertinent information without requiring user interaction. A capability like this could have a major impact on the savings of a centralized system. This capability can be used by the contractors to reduce their effort in documenting a model as well as reducing their charges to the Air Force to obtain a FEM.

This capability can insure improved adherence to the documentation standard format, since the software can control the format used. It will also reduce resistance of A. F. personnel to submit completed FEMs to the central system. Since the system will facilitate this documentation effort, it is just one more step to submit the model to the central system.

6.2.4 Expand The System To Accept Geometry As Well As FEM

The description of the centralized FEM system described in this report indicates storage of FEMs. The scope should be expanded to store "geometry only" if that is all that is available for a given a/c system. One of the most time consuming tasks in building an FEM is creating the 3-D computer based geometry from 2-D drawings. If the geometry is available on the system, some savings in model construction will be realized.

6.2.5 Existence Offers Low Cost Information

The existence of the system provides a mechanism to insure all appropriate design information for a given A/C system is obtained at the appropriate time, i.e., in the design phase of the project. A standard contractual agreement can be incorporated into all Air Force contracts that the design information be deposited in this central system for all development projects. This offers a high probability of assurance that some information will exist to build a FEM and will thus hopefully reduce the testing effort.

Also the central system offers the one and only location required to check for an existing FEM. This means the search time is reduced and thus the information obtained in less expensive.

6.2.6 Source For Technical Update Of FEM/FEA Technology

This centralized system will be an ideal training ground for organizations interested in studying computer systems communication issues. The system must evolve with new technology to stay functionally effective. As the Air Force moves towards integration of CAD/CAE/CAM, this centralized system will provide much insight into anticipatable problems.

This system can also be expanded to provide technical information on the latest techniques in FEM/FEA to Air Force engineers. The communications channels will already have been established so utilization of these channels to distribute technical information is an easy next step.

6.2.7 Potential For Expert System Applications In The Future

The electronic collection and manipulation of data is always a potential source for expert system applications. A number of applications exist, from operating the centralized system to automatically creating and analyzing FEM. This is definitely a future capability but the possibilities should be considered now.

6.2.8 Position The Air Force For Future CAD/CAE/CAM Integration

As discussed in the Trends section of this report, there is a continuing growth of integration of CAD/CAE/CAM in industry today. A system such as this could lay the groundwork for a Vertically (across applications) and Horizontally (across system commands) integrated CAD/CAE/CAM system throughout the Air Force.

7.0 CENTRALIZED DATABASE SYSTEM

A centralized database management system of USAF finite element models could provide a method of reducing costs in the present system. This database system is envisioned as a separate physical entity. It would probably be located at Wright-Patterson AFB because of the base's central location and the large number of SPOs that reside there. The system will have its own assigned work force. However, it is conceivable that this work force could have secondary responsibilities outside their centralized database duties. For security reasons, the information should be stored on a separate computer system which has limited access and may even be housed in a separate secured room.

In order to make a centralized database system feasible and efficient, the AF organizations requirements for FEMs and the categories and characteristics of information needed must be identified.

As discussed earlier, the Air Force has a wide range of applications for FEM; from large internal loads models of the entire aircraft (60,000 dof) to detailed models of a specific section of the wing (several hundred dof). The analyses represent a large spectrum of problems such as static, structural dynamic, aeroelastic, aerodynamic and heat transfer, but the majority of analyses are static. The breadth of FEM applications require the storage and processing of data which include static, time dependent, and frequency dependent, temperature dependent characteristics. The centralized database approach requires the standardization of both the format and content of model documentation and the format of finite element models.

The survey participants were asked if they thought a centralized database of finite element models would be a more effective approach for conducting finite element analysis than the present method. Seventy percent (70%) of the organizations felt that a centralized database of finite element models would provide a more effective approach. The dissenting opinions were voiced from three of the ALC's: (1) Ogden ALC/MMARA, (2) Sacramento ALC, and (3) Warner-Robins ALC.

The negative response was influenced by the nature of their duties. They are responsible for a particular system and generally have need for unique applications for FEM that may be in response to a particular problem on their assigned aircraft. Other reasons given for deciding against a centralized database system were: (1) didn't feel anyone else should have a need for FEM of their assigned aircraft, e.g. SM-ALC didn't think anyone besides them would have a need for F-111 or A-10 models, (2) FEM developed by others are often hard to understand because the thought process of the modeler is difficult to convey, (3) different applications required different meshes, and (4) thought the models should be obtained by the SPO then transferred to the ALC along with responsibility for the system. These ALCs also have or will have all of their contractor developed models "on-line" at their site. A provisional affirmative response was received from 4950th Test Wing which indicated that at present most of their applications wouldn't be helped since the FEMs they need probably wouldn't appear in the database. However, they still have some tasks that could be aided if the screening procedure for FEMs in the database were quick and easy.

On a positive note, there were organizations which were interesting in keeping abreast of the conclusions of this study and the development of a database system if it was deemed feasible. The 6520th Test Group was interested in the database system for several purposes: (1) obtaining computer aircraft models from other AF groups which do similar types of analysis such as Eglin AFB; and (2) verifying the vendor's analysis and checking to see if AF specifications were met. The Test Group is mainly interested in entire aircraft models for flutter analysis. Eglin AFB has a group that does store testing and would have need for similar FEMs. They also feel that having access to vendor created FEMs would allow them to analyze "on-site" modifications of the aircraft with relative ease.

There are numerous reasons to consider the implementation of a centralized database system for finite element models. A properly design FEM database system would: (1) eliminate the duplication of monies spent on purchasing models from the contractors, (2) reduce manpower necessary for the procurement of models, (3) reduce cost of locating finite element models within the AF organizations, and (4) possibly reduce some testing costs. There are also other advantages of a centralized database that are hard to quantify in terms of dollars: (1) a centralized location for the storage of finite element information, (2) facilitate management of information, (3) data format standardization would reduce the format incompatibilities for data transfer activities, and (4) reduction FEM delivery times.

7.1 Preliminary Centralized Database System

7.1.1 Technical Approach

The preliminary centralized database system would be modular in nature to provide the greatest flexibility for future updates and modifications. A conceptual database is shown in Figure 7-1. There would be at least six modules: (1) Executive Module, (2) Cataloguer Module, (3) FEM Run Deck Module, (4) Interactive Graphics Module, (5) Translator/Interface Module, and (6) Analysis Module. The functions of these modules are subsequently discussed. This approach would allow the system to take advantage of as much applicable existing software as possible and reduce the amount of software that must be developed.

Figure 7-1 shows solid lines which link the Executive module to all other modules in the system except for the Cataloguer module. The dashed lines in the figure indicates that there will be some link between the Cataloguer and the rest of the system, but the Cataloguer module could possibly be on a separate machine, perhaps even a personal computer (PC). The reason to have this module separated from the rest of the system is because of potential security issues of future aircraft configurations. If sensitive or classified material is stored in this system, then there must be only limited access to the finite element information. There can be no modem lines into the machine. The Cataloguer module should provide the engineer with enough information to determine if a FEM is usable for his application. It could also supply interested AF personnel with a quick link to the FEMs in the system without access to the sensitive information.

The Executive module would be the user interface module and would control interfacing to other modules. The user interface should be designed so that it is "user-friendly" and it would probably be menu driven so that the user can navigate by pointing at menu items. Unprompted requests for more familiar users could also be accommodated. It would have an input command processor which could handle language syntax, prompt the user, and display messages. The Executive module would also manage the input of information to the database system. It is proposed that the database will have several methods of inputting data: (1) magnetic tape, (2) keyboard input, and (3) scanner. In most cases, FEM quantitative information such as FEM analysis run deck and pre-processor files would be transferred using magnetic media. The keyboard would be used to manipulate the data and the various modules of the system. The scanner could be used for transferring both text and figures. The Executive module might also be the sole link to Cataloguer module. Some query and data management capabilities could also be available. An "on-line" help system with examples could facilitate use of the system. The

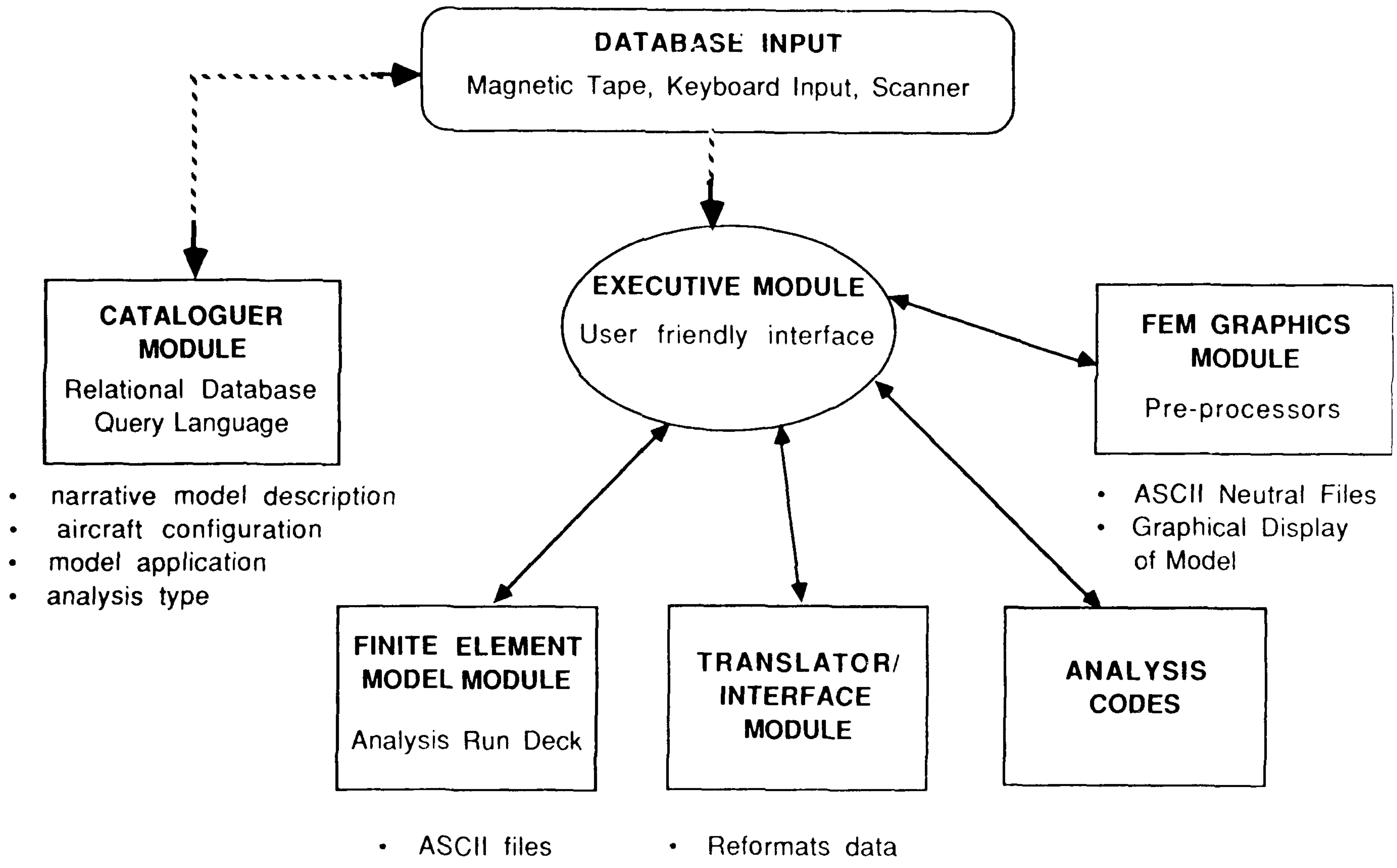


Figure 7-1. Conceptual Database System Architecture

Executive module would probably only be used by the personnel who are physically located at the site of the centralized database system.

The Cataloguer module would function in a similar manner as a computerized bibliography search available at most libraries. This module would be menu driven with "on-line" simplified instructions so that the user need not be burdened with a lot of the system details. It would be an electronic card catalogue of information about the finite element models in the centralized database system. Instead of having author, subject and title cross-reference categories, the database system would have categories such as an index of aircraft models, FEM summary, FEM description, model source information, FEM graphics, etc. The relationships between categories of data might be as shown in Figure 7-2. A display of the aircraft configurations which have FEMs in the system could be displayed on the screen as shown in Figure 7-3. The round rectangular boxes are selectable items which the user can choose by pointing to them with cursor. In this example, there are many configurations available: A-10, B-1, B-52, F-15, etc. If the user would like to see what models are available for the XYZ Missile, then he would select the appropriate box. (The XYZ Missile FEM has been selected in Figure 7-2.) If the user wanted help or to see other configurations for which models are available, he would point to the help box or the right facing arrow, respectively. The actual models available for a particular configuration could then be perused by flipping through a stack of finite element model summary cards. The user could also search through the title with appropriate keywords such as booster adapter.

An example of the typical contents of a summary card for the XYZ Missile Booster Adapter Modification 2 is shown in Figure 7-4. The intent of this card is to give the user a brief flavor for the model by providing a title which would include the component modeled and by highlighting what the purpose of the analysis was, the solution type and the analysis code used. The information in this example was taken from an actual analysis done on an aerospace structure by PDA. If this model is of interest to the user or if more information is desired, the user could select any one of the tabs on the index card, for example description, figures, source. The summary, description, figures, and source stacks of data could all be linked to each other as indicated by the double headed arrow lines in Figure 7-2.

When the description button is selected, the FEM description card would pop up on the computer terminal (see Figure 7-5). The description card would have some header information which could include what card type, configuration, and model title. The model description should include a brief description of the physics being simulated, i.e., a discussion of the structure, loads, boundary conditions, boundary conditions, and any unique modeling approaches which might be

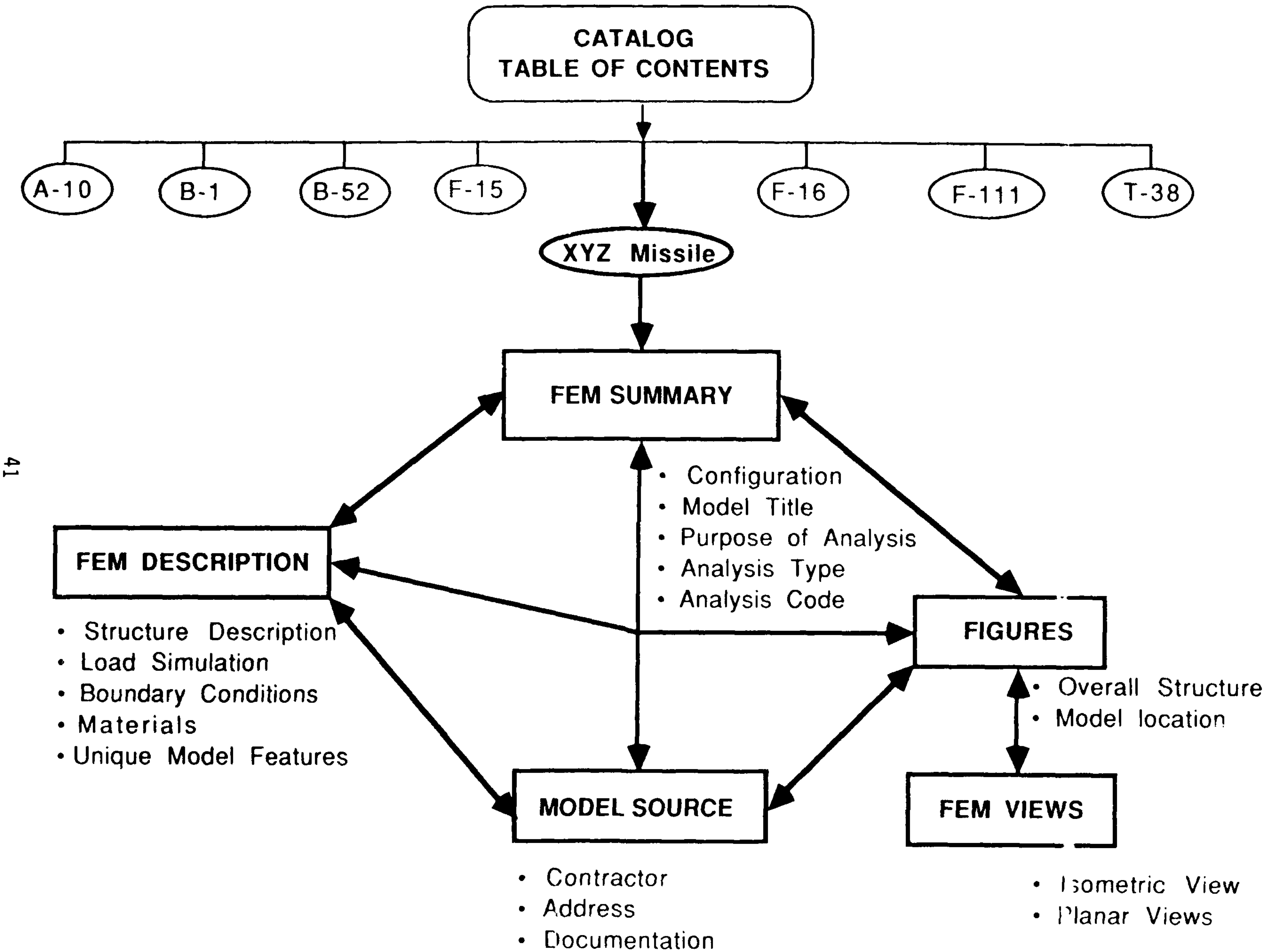


Figure 7-2. Finite Element Models Catalog Flowchart

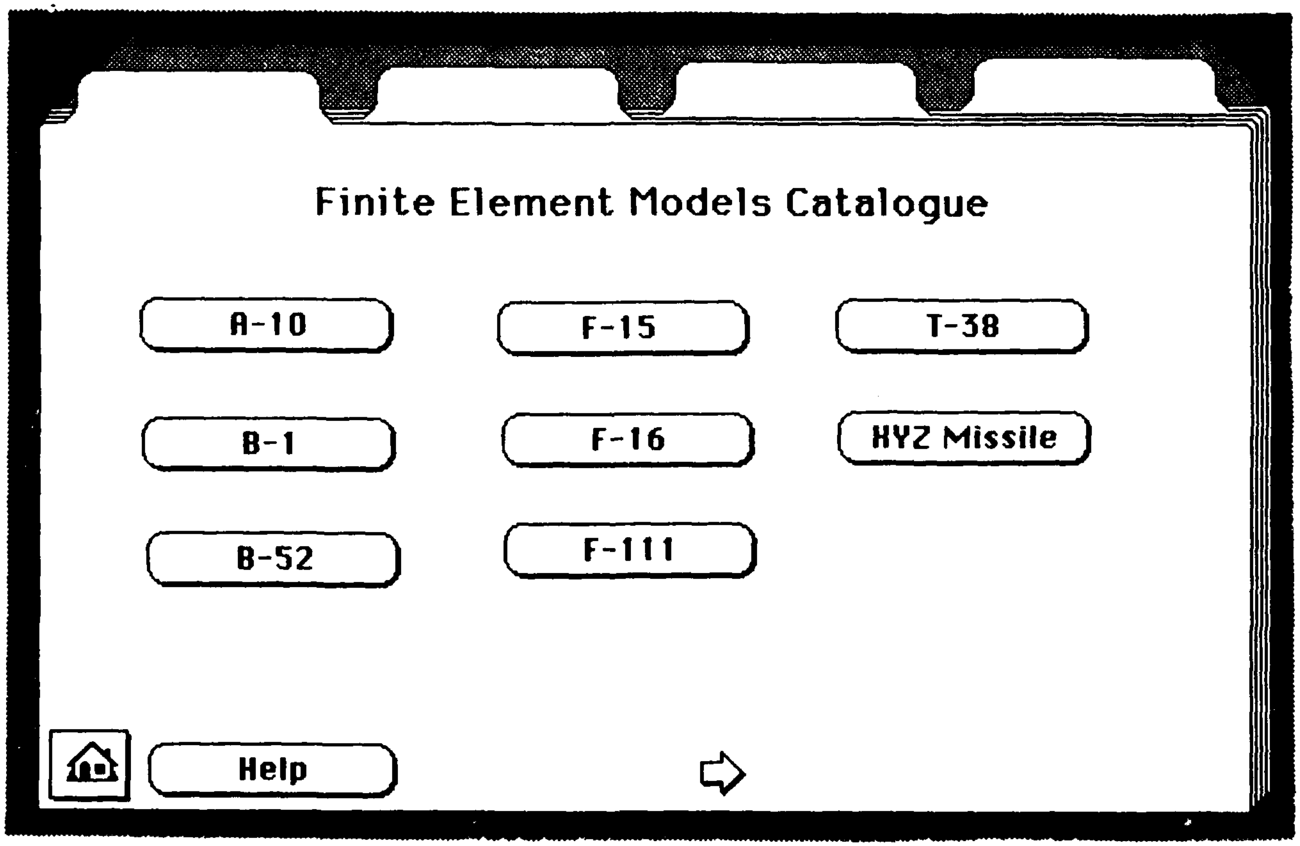


Figure 7-3. Finite Element Models Catalogue Table of Contents

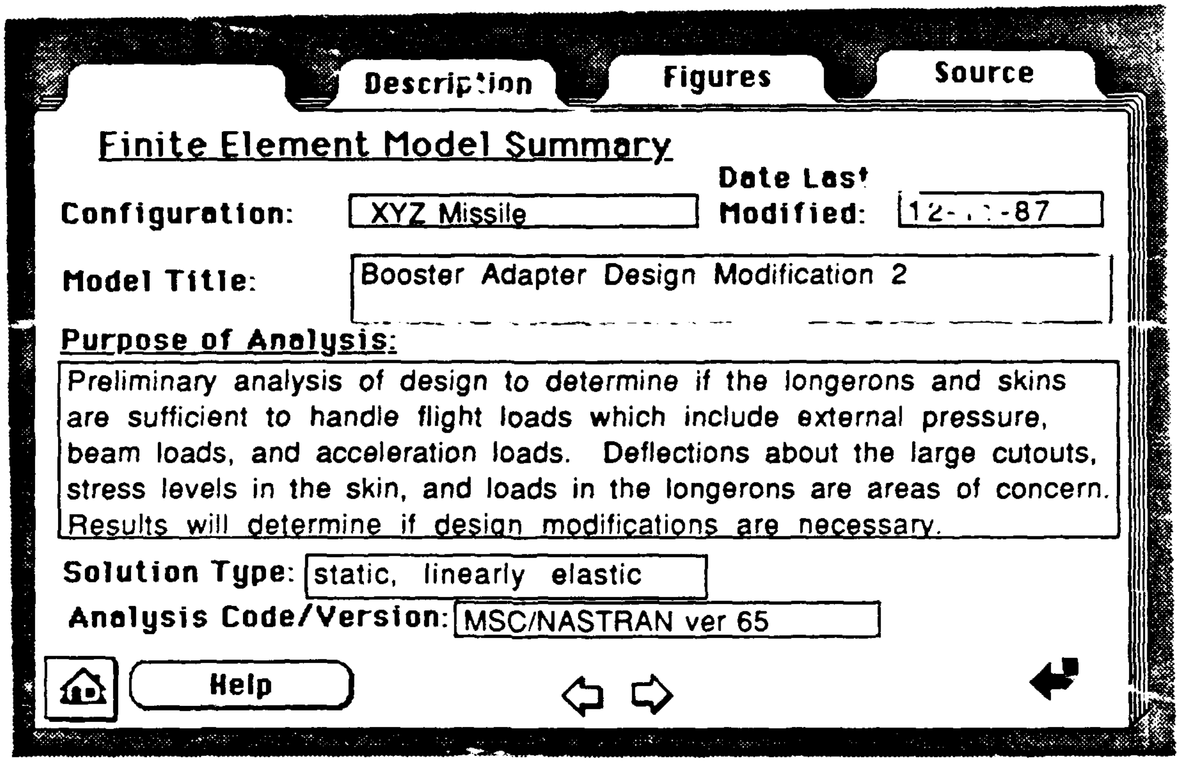


Figure 7-4. Finite Element Model Summary Card Example

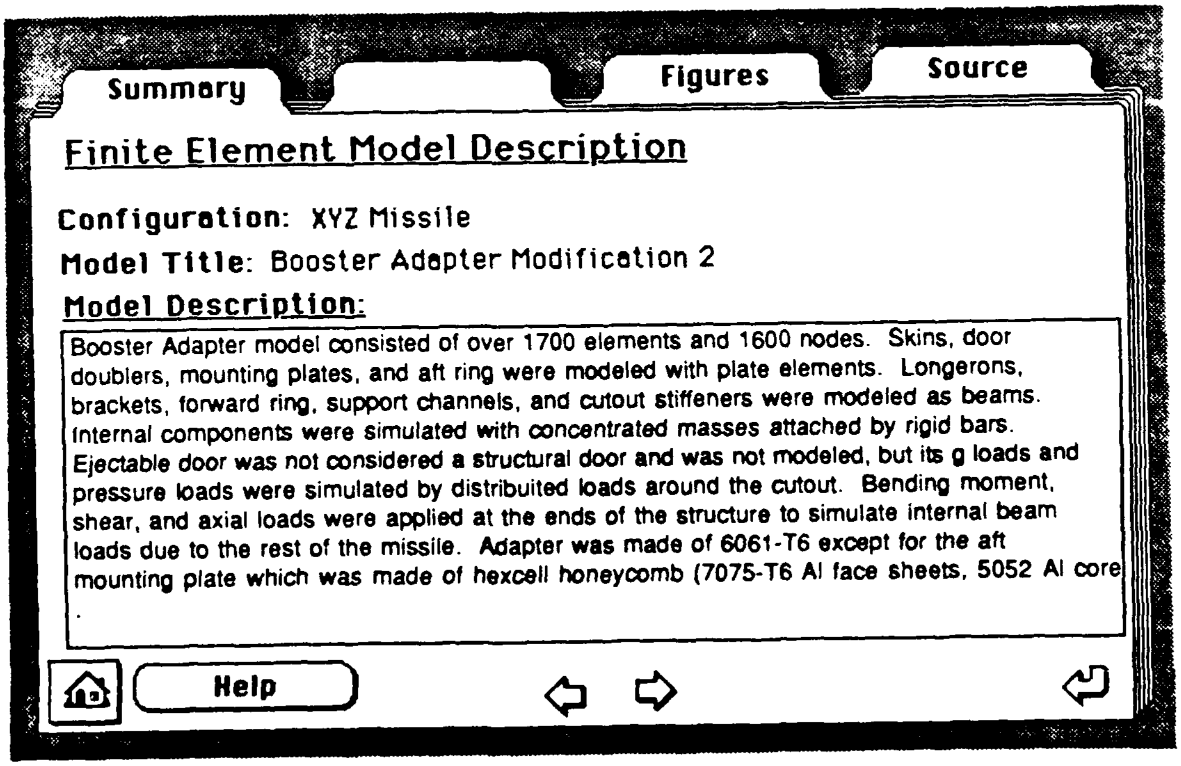


Figure 7-5. Finite Element Model Description Card Example

useful to a perspective user. Additional space for the model description could be obtained by a request from the user.

An example as to the possible content of a FEM model source information card is shown in Figure 7-6. It would list the contractor (or other appropriate source) from whom the model was obtained, their address and any documentation relevant to this model. Figure 7-7 shows an example of the graphical information which might be stored in the catalogue. The header information is the same as was seen on the previous card. This figure shows the overall structure, XYZ Missile profile, of which the booster adapter is a component. The location of the booster adapter is highlighted by a dashed ellipse.

If the user wishes to see the actual finite element model then the "FEM Views" button must be selected. Figures 7-8 and 7-9 show an isometric and planar views of the booster adapter, respectively. These figures could quickly convey to the perspective user what the model looks like. These views would be predefined by an engineer at the database site. There would be no explicit geometry data available. The FEMs displayed would be scaled to some unknown scale. The user should also be able to inquire if the finite element analysis run decks and/or a pre-processor file is available and what pre-processor was used. Cross-referencing between various data fields and searching for user specified keywords throughout the data would be a useful utility. The graphics could be input to the catalogue via a scanner. All information stored by this module should be approved for wide dissemination throughout the AF, i.e., there should be no sensitive material stored in the catalogue.

The Cataloguer module may take advantage of a software program like HYPERCARD (Apple software) which used indexed stacks and can have graphics interspersed within texts. The examples of data categories shown in Figures 7-3 through 7-9 were done using HYPERCARD. The graphics can be input to the Cataloguer with a scanner using bit mapping. This would require each AF site to have a some type Personal Computer (PC). However, this would provide a method of controlling data access. The electronic catalogue of the finite element models could be distributed to various sites on 3 1/2 inch floppy disks. The catalogue could be updated on a periodic basis and then redistributed to the interested parties. HYPERCARD provides fast and easy retrieval of data. The cross referencing can be done by pointing to a category or button. Another advantage of using this approach is that the catalogue can probably be used with little or no training. All of the cross referencing selection are simple picks that can be identified with icons or buttons. PCs can communicate easily with VAX hardware. This would also alleviate the graphics device compatibility that would be needed to provide graphics images over the phone.

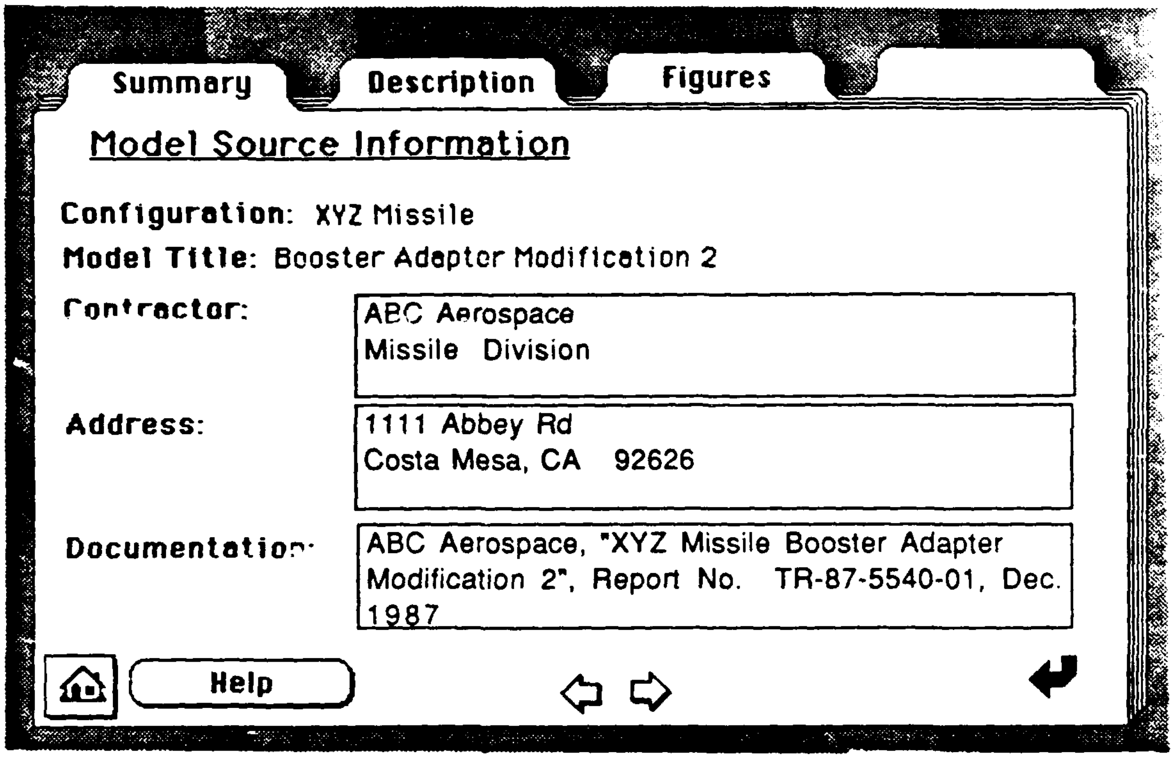


Figure 7-6. Model Source Information Card Example

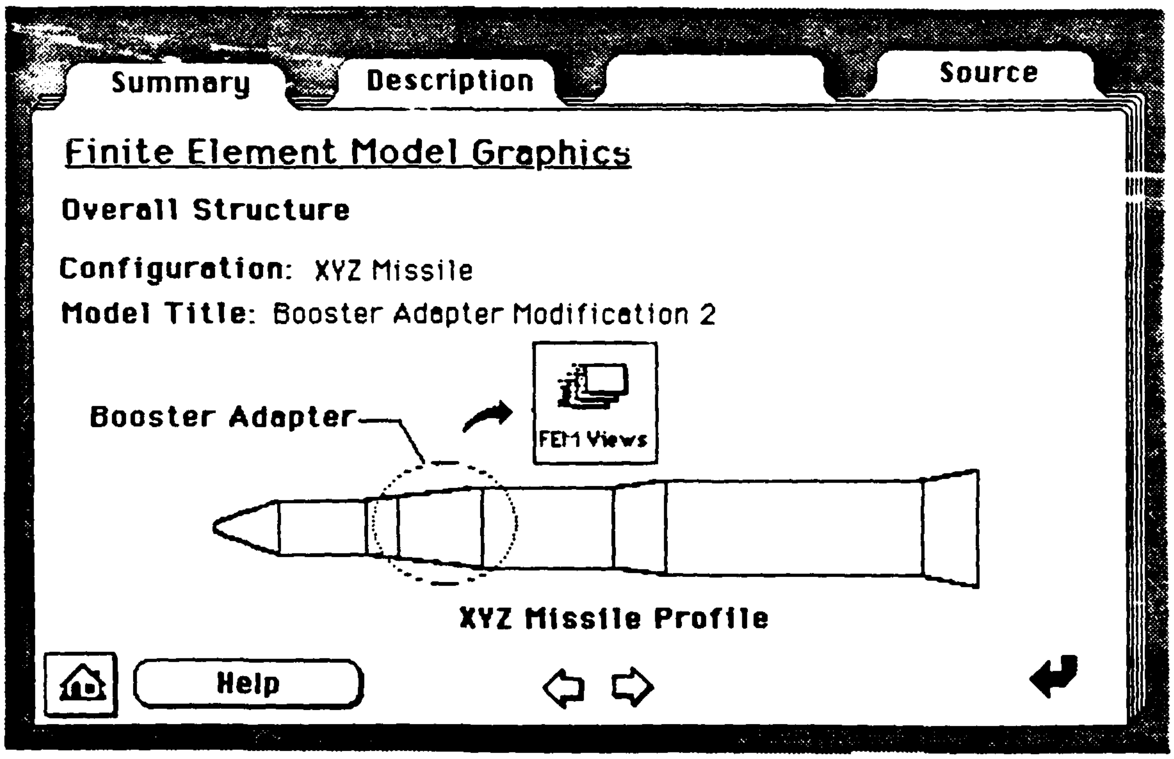


Figure 7-7. Finite Element Model Graphics Card Example

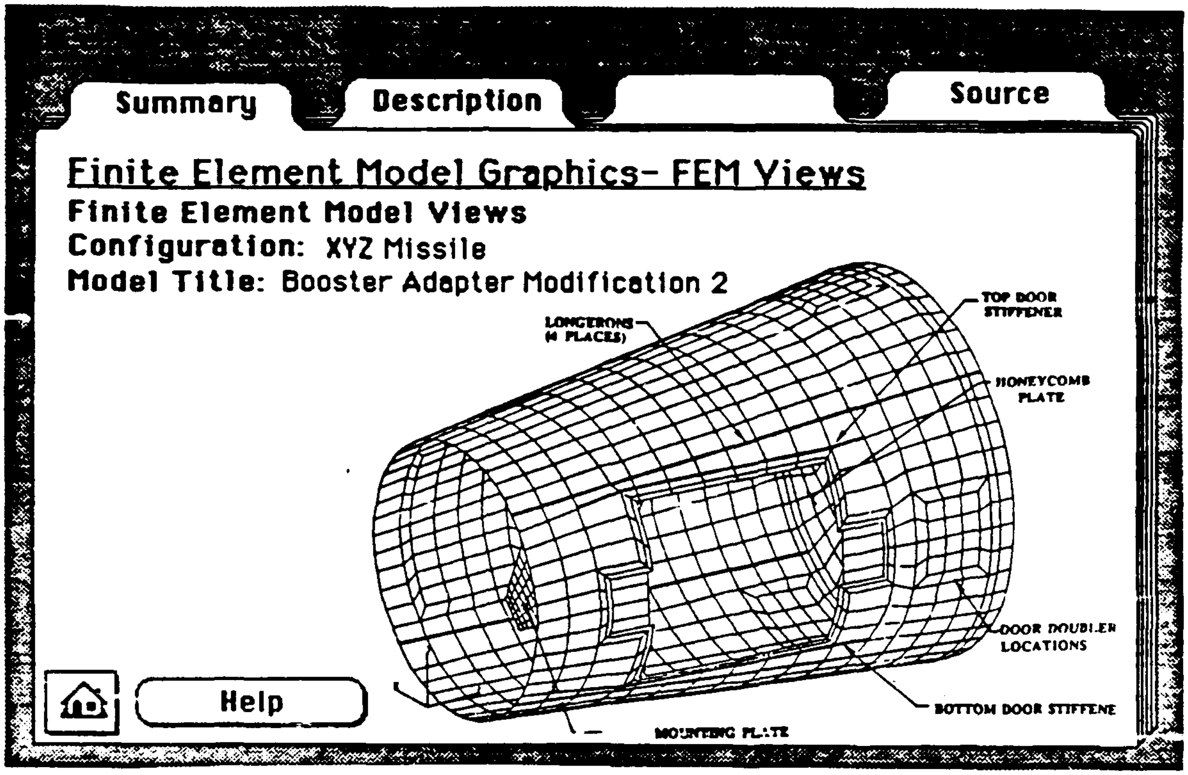


Figure 7-8. Finite Element Model Isometric View Card Example

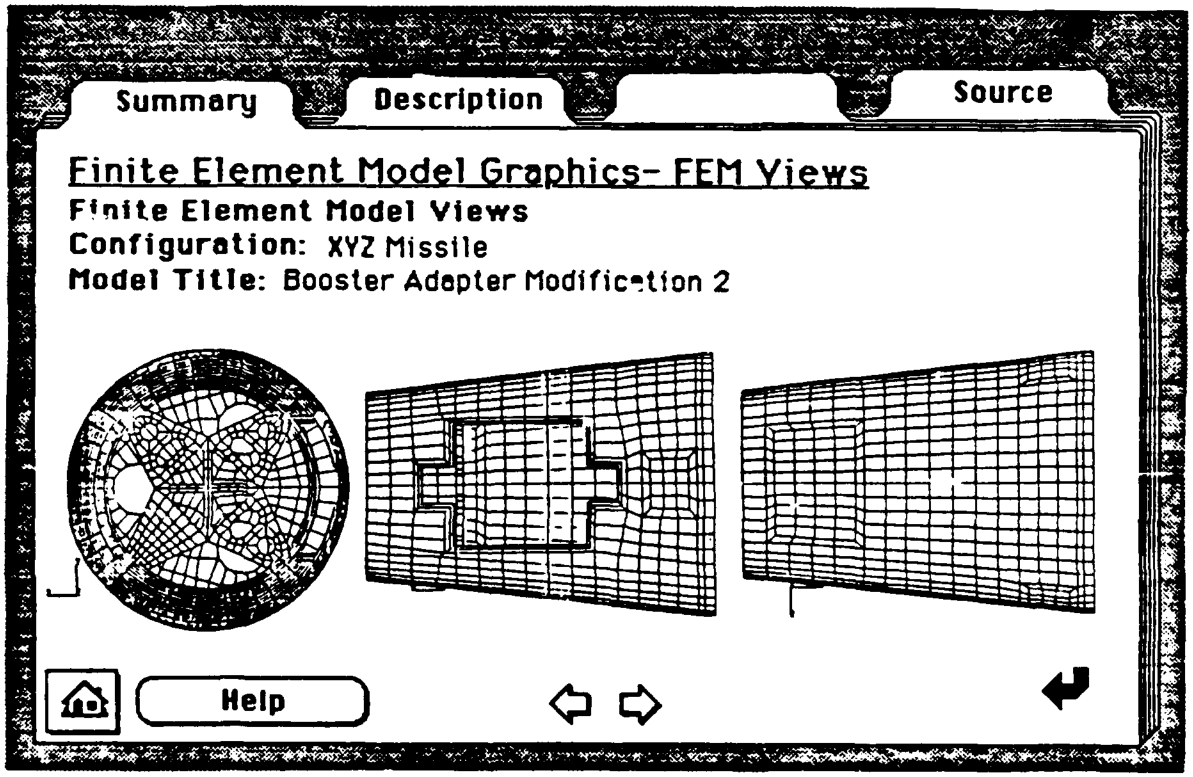


Figure 7-9. Finite Element Model Planar Views Card Example

The Finite Element Model Run Deck Module would be used to handle the information in analysis run decks format. It would be a simple indexed storage of FEM information whose existence could be pointed to by the Executive module. Most of the models which have been purchased by the Air Force from various contractors were received in analysis run deck format, e.g., for MSC/NASTRAN this would include the Bulk Data Deck, Case Control Deck and the Executive Control Deck. In order to render a graphics display of the model, it will be necessary to process the data through some software. The analysis run decks are 80 character ASCII card image files. Translators are commercially available that can take the information in a run deck and then convert the data to a format which is usable by a interactive graphics pre- and post-processor. For example, to convert a MSC/NASTRAN run deck to a PATRAN neutral file, the user would run NASPAT. This file could be read into PATRAN and a graphic display of nodes and elements would be seen on the graphics terminal. It is important to store this information because the analysis deck has the actual loads, boundary conditions, and material properties for a particular structural response scenario. Even with state-of-the-art translators there will often be cards which must be manually input by the modeler for one reason or another. It is important to get the actual run deck which was used to meet the AF specifications and validated with test results. If the model is completely understood by the analyst, then simple modifications can be made directly to the deck and reanalyzed.

The Interactive Graphics Modules will contain at a minimum PATRAN and GEOMOD, the most popular pre-and post-processors, used throughout the polled Air Force Organizations. Sixty percent (60%) of the respondents have or will have PATRAN and forty percent have GEOMOD (SUPERTAB). In addition to these tools, 50% of the organizations have other pre-and post-processors such as CADS, GIFTS, GRASP, and GRAFEM. This module will be used mainly by the personnel on site to decipher and validate models as they are delivered. Since FEMs are created with pre-processors, a universal or neutral file format (GEOMOD or PATRAN) will also be required as a deliverable. The PATRAN neutral file is a well documented file that has 80 character ASCII card images whose data can be easily reformatted into a specific analysis code format with a translator. The advantages that pre-processor files have over the analysis run decks are they possess a more detailed geometric description of the structure and geometry and/or finite element meshes can be more easily modified. The information will approach more closely the idea of a "master model" alluded to in the original Phase I SBIR solicitation.

It is next to impossible to have a single master model that would address all Air Force FEM applications. For instance, a flutter model of the entire aircraft would be a stick (beams) model while an internal loads model requires plates and beams. The geometric entities required would be lines and surfaces and lines, respectively. When pre-processor files are transmitted to the database

system, there should be some form of narrative documentation which relates element and nodes which are described by FEM documentation to geometric entities such as lines and surfaces. In terms of PATRAN notation, the nodes and elements could be grouped together with the geometric entities which were used to generate them in "named components", (A collection of PATRAN entities which are given a relevant alphanumeric name).

The Translator module would provide a communication link between pre- and post-processor and analysis codes. Translators also provide a method for using the data in an analysis run deck to create a graphics display of the module. The Translator Module will provide the function of reformatting information into a format usable for the selected analysis codes. Translators already exist to format data from PATRAN to MSC/NASTRAN or ANSYS, etc. and from GEOMOD to MSC/NASTRAN. These translators support the majority of the applications used in industry. However, there are options which are not supported and must be manually inserted into the deck by the analyst. Translators allow great flexibility of reformatting data from one code to another but at present do not have a check to see if the element types or cards are directly compatible between codes. The burden of element compatibility would still be upon the shoulders of the user.

The Analysis Code module would provide the "on-line" computational capability. MSC/NASTRAN and COSMIC/NASTRAN would probably be available since eight out of 10 (80%) of AF organizations use MSC while 6 of 10 organizations (60%) use COSMIC.

7.1.2 Management of the Centralized Database System

The management of incoming and outgoing of data is of concern because of need to control distribution of information. There are two competing issues when it comes to determining the accessibility of the information stored in a centralized database system: (1) security, and (2) reasonable access by authorized individuals. Although it is necessary to safeguard the information from parties who don't have the "need to know", it is also important to make the data reasonably accessible to individuals who have the "need to know". The centralized system must be more efficient than the present system in determining the existence of a finite element model.

It is envisioned that the model description stored in the cataloguer and some form of graphical display will be directly accessible to all approved Air Force organizations (as discussed in Section 7.1.1). However, the actual finite element models in analysis run deck format and/or pre-processor format would be stored "off-line". Thus limiting access to that information to personnel which work at the site for the centralized database system.

The centralized database system would have restricted access as shown in Figure 7-10. The dashed lines indicate that each AF organization would have access to the Cataloguer module

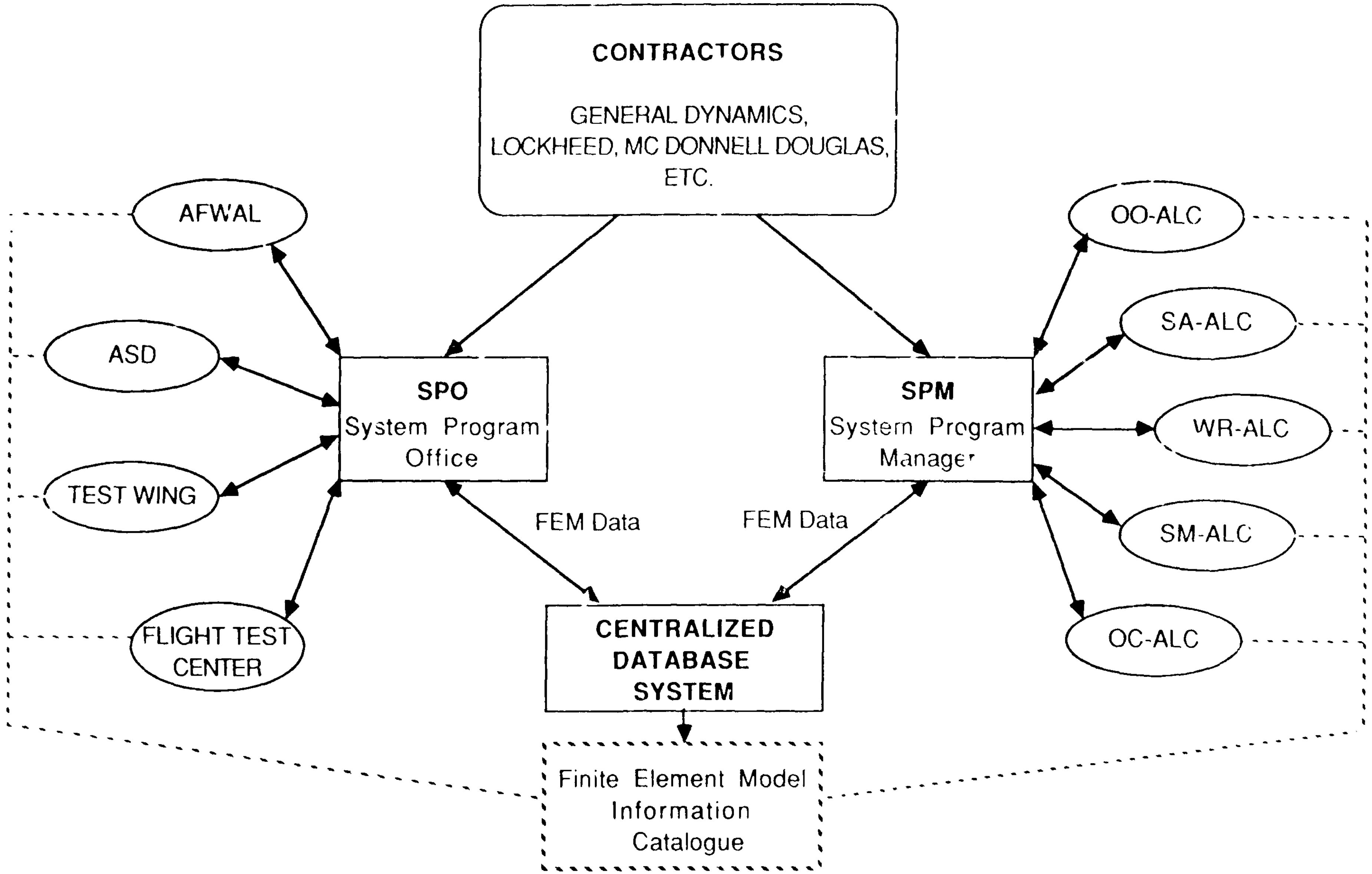


Figure 7-10. Centralized Database Access Flowchart

but not direct access to the FEMs. The FEMs would be distributed via magnetic media. If security access must be controlled it could be controlled by the System Program Office (SPO) and System Program Manager (SPM) and the AF personnel could request information from the SPO or SPM. Otherwise some type of security function would have to be maintained at the centralized database site.

7.1.3 Finite Element Model Standards

Presently, there are no formal AF standards for finite element model information. The Data Item Description (DID), entitled Data for Finite Element Models of Aerospace Structures, which has been put together by AFWAL/FIBRA is a starting point for these standards (A copy of the DID is included in Appendix B). As more information becomes available through this SBIR effort and other studies involving finite element information, this DID can be updated and enhanced.

In order to make the centralized database system a viable alternative to the present system, some standardization is necessary. In most cases, the standardization of information will facilitate the handling, storage and retrieval of the data . Not only should there be guidelines as to content of finite element documentation but there should also be a format standardization.

One possible method to provide a minimum level of format standardization is to have a summary sheet of the finite element information. An example of a summary sheet is shown in Figure 7-11. This will provide a level of commonality between all FEM to be entered into the database. It could also be compatible with the input to the FEM catalogue of information.

The information stored on this sheet could be entered into the database system through two possible methods: ASCII character file on magnetic tape whose format is predefined by an AF standard or through a scanner. In both cases, some software must be written to handle the data input to the system to provide some level of automation. The FEM summary data processing software could be written by an AF funded effort and then distributed to the appropriate contractors or a specification for the file format could be a contract item. In the second case, when a scanner is used once the information is entered into a standardized form and scanned into a text file the data could be manipulated with some software written expressly for this purpose. The standardized form would be a part of a contractual requirement.

The FEM descriptors on the Finite Element Model Description Summary (Fig. 7-11) along with selected views of the model should give the potential user a good idea of whether the model is applicable for his purposes. Also note that the FEM Description Summary categories correspond to those used in the catalogue information example discussed in Section 7.1.1.

FINITE ELEMENT MODEL CHARACTERISTICS

1. CONFIGURATION (e.g., F-15A)	2. DATE LAST MODIFIED	3. DATE

4. MODEL TITLE (component modeled)

5. PURPOSE OF ANALYSIS (e.g., determine effect of adding a weapon on flutter characteristics of wing)

6. SOLUTION TYPE (e.g., static, modal)	7. ANALYSIS CODE AND VERSION

8. LOADING TYPE (e.g., static, transient, pressure, forces, displacements, temperatures)

MODEL DESCRIPTION

10. KEYWORDS (e.g., wing, flutter)

11. MODEL DESCRIPTION (Summary description of physics being simulated, i.e., structure, materials, loads, boundary conditions)

MODEL SOURCE

12. CONTRACTOR	13. ORGANIZATION	14. REPORT DOCUMENTATION

14 MAILING ADDRESS (P.O. Box, Street, Mail Station)	15. CITY	16. STATE	17. ZIP CODE

Figure 7-11. Finite Element Model Description Summary

Figure 7-12 is an example of the data content which could be useful to a potential user of the XYZ Missile Booster Adapter. The purpose of analysis and model description information are the most critical categories along with figures that will determine if a FEM is applicable.

Figures 7-13 and 7-14 show the actual finite element mesh used in the linearly elastic static analysis run on MSC/NASTRAN. Figure 7-13 shows an isometric view of the model looking towards the ejectable door location. The majority of the structure was modeled with plate elements. Various portions of the model were shaded to indicate different thickness plate elements. The longerons and door stiffners were modeled with beam elements and denoted by the darkened lines which run in the axial direction of the structure. Pertinent structural components are also noted along with their location. Figure 7-14 shows three planar views of the model along with the same isometric view. These views are used to convey the arrangement of structural components, meshes used, and the shape of the structure. The first frame in this figure shows a view from the front looking towards the aft. This allows the reviewer to get a overall view of an internal mounting plate (its lightening holes) and its orientation relative to the aft honecomb plate and its cutouts. The next two views illustrates the shallowness of the cone angle and mesh used for the shell as a function of circumferential location.

The previous three figures are important to the development of AF standards because they can convey to potential model users the information content which is required for "acceptable" documentation. PDA feels that the categories and documentation in current specifications are good but that they can be further enhanced by including typical examples for certain categories for each of the analysis types. Probably the most important solution type to document is the static analysis case because of the widespread use throughout the USAF, but example documentation is important for the other analysis types, too.

The detailed documentation could appear in report format. The report reference number would appear on the summary sheet. The contents of the report should follow the guidelines set in the DID. Under the general requirements section of the DID, the purpose of the analysis should be added. This description alone could determine, in a general sense, why the coarseness of a particular mesh was used, or why certain boundary conditions were used, or why certain geometric details were ignored, or in our example, the booster adapter model, why the internal components were attached with rigid bars instead of providing a flexible attachment. In the booster adapter model, the analysis was a check of structural integrity of the design to see if it could withstand the flight loads. The longeron loads and the skin stresses were of primary concern. It was important to get the influence of the inertia loads of the internal components into the structure without going in great detail. Thus rigid bars were adequate for this purpose. If the first analysis had shown unacceptable stress levels at the point of attachments, a different modeling strategy would have been used and the model would have been appropriately modified.

FINITE ELEMENT MODEL CHARACTERISTICS

1. CONFIGURATION (e.g., F-15A)	2. DATE LAST MODIFIED	3. DATE
XYZ Missile	12-11-87	1-10-88

4. MODEL TITLE (component modeled)

Booster Adapter Modification 2

5. PURPOSE OF ANALYSIS (e.g., determine effect of adding a weapon on flutter characteristics of wing)

Design analysis to determine if structure can "worst case" flight loads which pressure, acceleration, and beam loads. Deflections around large cutouts and stress levels in structure, and longeron loads are of concern. Results will determine if design modifications are necessary.

6. SOLUTION TYPE (e.g., static, modal)	7. ANALYSIS CODE AND VERSION
static, linearly elastic	MSC/NASTRAN ver 65

8. LOADING TYPE (e.g., static, transient, pressure, forces, displacements, temperatures)

static; pressure, acceleration, forces, moments

MODEL DESCRIPTION

10. KEYWORDS (e.g., wing, flutter)

missile, booster adapter, flight loads, static, linear elastic

11. MODEL DESCRIPTION (Summary description of physics being simulated, i.e., structure, materials, loads, boundary conditions)

Model consisted of over 1700 elements and 1600 nodes. Skins, door doublers, mounting plates, and aft ring were modeled with plate elements. Longerons, brackets, forward ring, support channels, and cutout stiffeners were modeled as beams. Internal components were simulated with concentrated masses attached by rigid bars. Ejectable door was not considered a structural door and was not modeled, but its g loads and pressure loads were simulated by distributed loads around the cutout. Bending moment, shear, and axial loads were applied at the ends of the structure to simulate internal beam loads due to the rest of the missile. Adapter was made of 6061-T6 except for the aft mounting plate which was made of hexcell honeycomb (7075-T6 Al face sheets, 5052 Al core).

MODEL SOURCE

12. CONTRACTOR	13. ORGANIZATION	14. REPORT DOCUMENTATION
ABC Aerospace	Missile Division	TR-87-5540-01, Dec 1987

14. MAILING ADDRESS (P.O. Box, Street, Mail Station)	15. CITY	16. STATE	17. ZIP CODE
1111 Abbey Road	Costa Mesa	CA	92626

Figure 7-12. Finite Element Model Description Summary Example

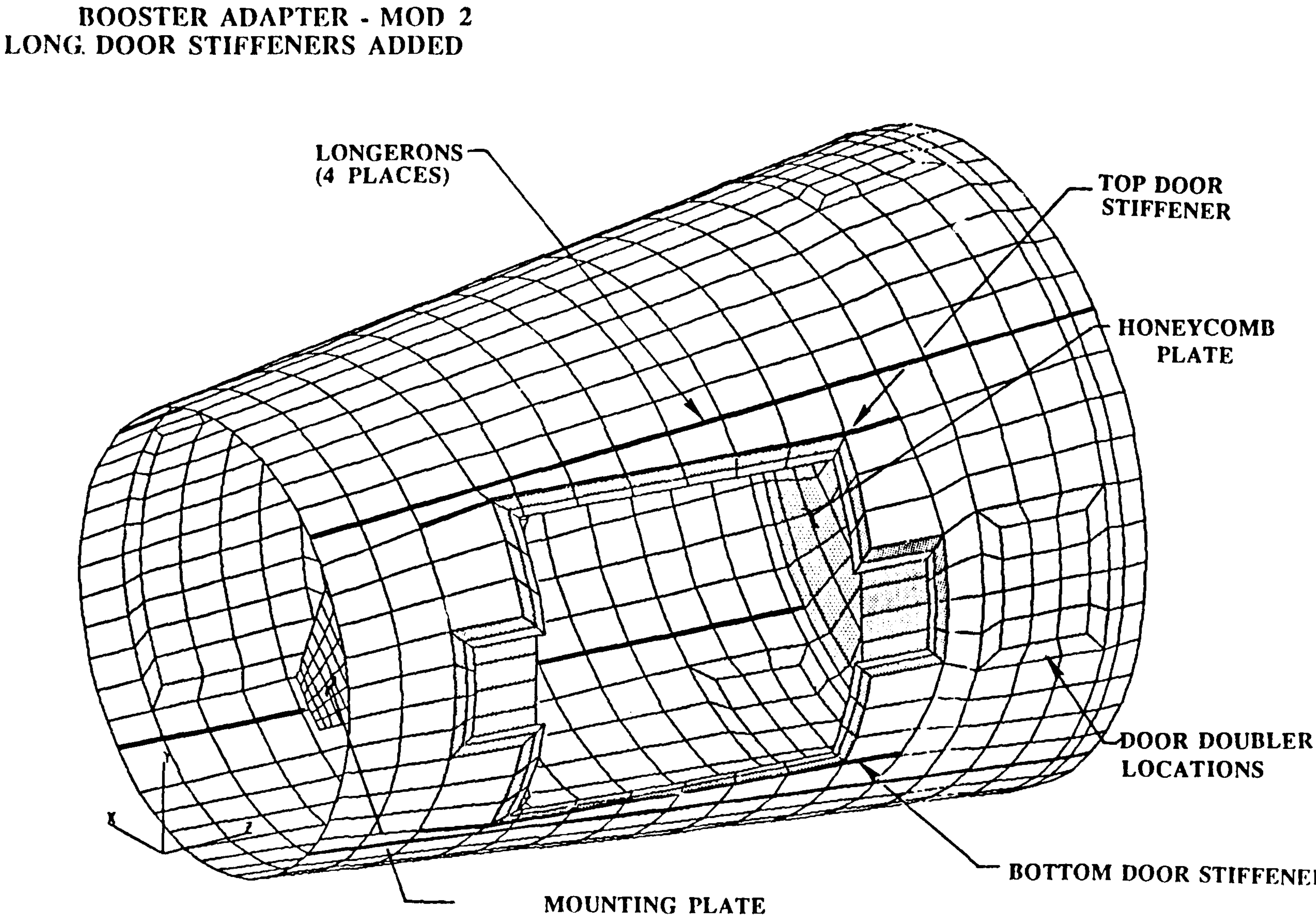


Figure 7-13. Finite Element Model - Isometric View Example

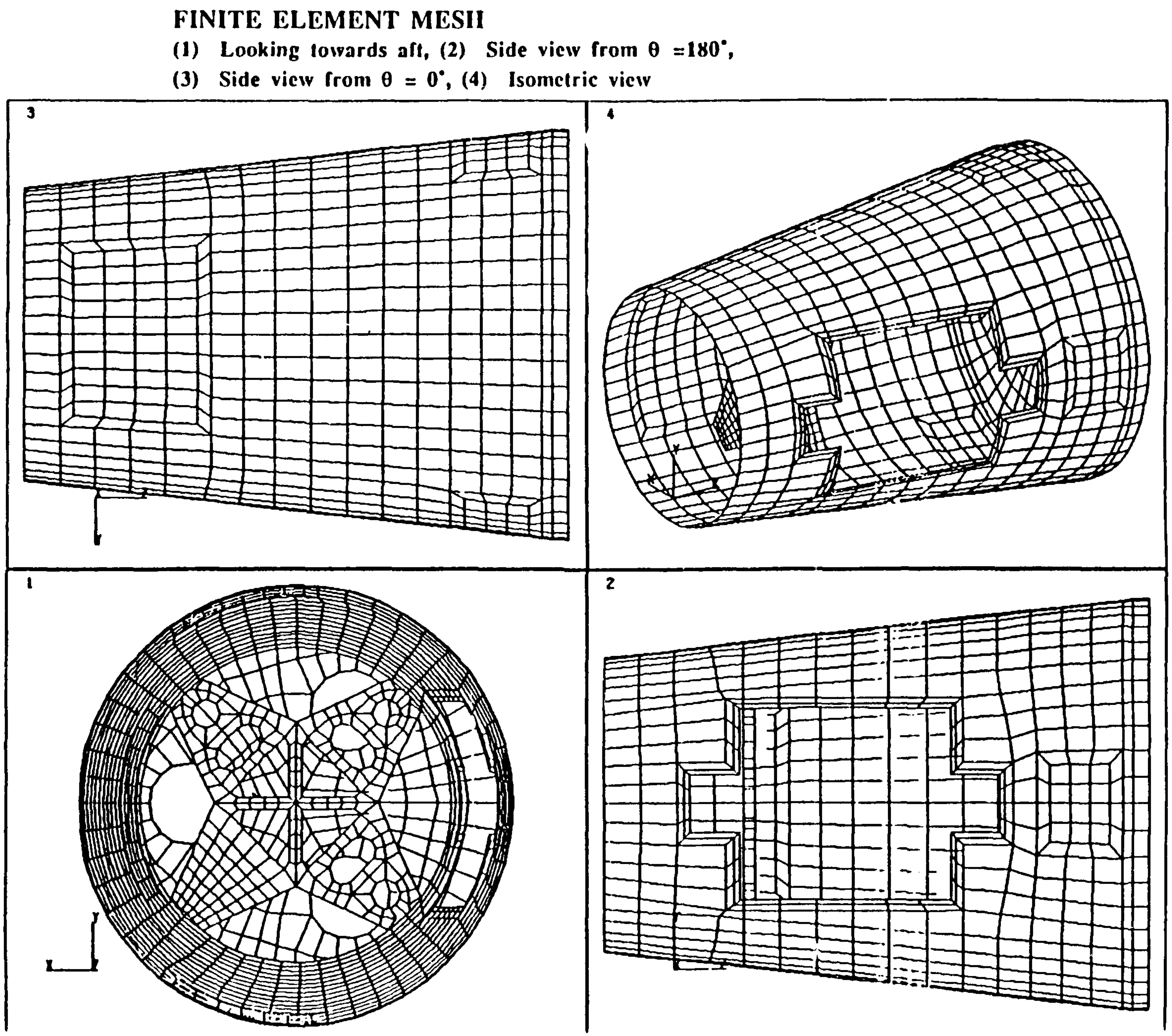


Figure 7-14. Finite Element Model - Multi-View Example

Finite element modeling and analysis allow great flexibility in the approaches used to solve a problem. Thus, it is important that the thought process of the modeler be documented in some manner so that it can be conveyed to any future user. There are assumptions and approximations that are made in order to create a reasonable finite element model, i.e., one that has enough detail to provide both the correct stiffness and good stress results and be capable of running on the available computer resources. There are liberties which each analyst takes in modeling the structure which are dependent to some extent on the application and the results of interest. Some types of models require more documentation that others. In fact, it seems that the level of documentation about a model is inversely proportional to its dimensionality. Three-dimensional solid elements model the stiffness implicitly by their volume and material properties. In two-dimensional elements, it is necessary to enter some of the physical properties of the plate such as thickness, or equivalent stiffness parameters. One-dimensional elements require yet more physical characteristics to be defined and calculated by the user explicitly. These characteristics include cross sectional area, moments of inertia, beam axis orientations, beam offsets, and stress recovery points.

The following discussion is a sample of the type of documentation which should be required from the contractors when they use beam and equivalent thickness plate element. For the booster adapter model, it would be useful for a potential user to have a sketch of the cross-section with calculated properties used for the longerons and door stiffness (see Figure 7-15). The booster adapter also had a honeycomb plate which was made of 7075-T6 Aluminum (Al) face sheets and 5052 Al hexcell (0.125" dia. cell) core. This plate was modeled with an equivalent plate thickness equal to the combined thicknesses of the face sheet. A sketch of the honeycomb plate cross section is shown in Figure 7-15. Equivalent bending and shear thicknesses were calculated using the equations shown in Figure 7-15. These equations can be found in Hexcel Honeycomb Sandwich Design Brochure E[11,12]. Appropriate references should also be sited for unusual section property calculations and material properties.

A description of boundary conditions, loads and the rationale for selecting load orientation when specified contractually could also help in assessing the model. Figure 7-16 shows the beam loads which were applied to the forward end of the booster adapter. Although the magnitudes of the axial, shear, and bending moment were specified as 3510 lb, 1260 lb, and 41,920 in-lb, respectively there were no load orientations specified. PDA selected the orientation based on its past experience with similar structures, which dictated that the "worst case" shear load be orientated perpendicular to edge of the cutout. The orientation of the bending moment was chosen so it would complement the shear loads effects.

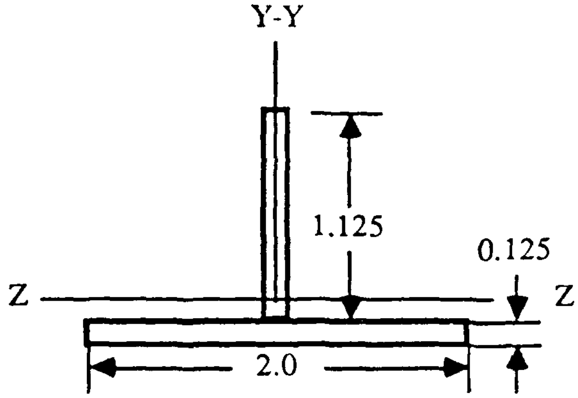
The content of what a FEM should include is fairly well covered in the DID. The entire run deck should be included as a deliverable i.e., the file which is delivered to the Air Force should run on the same code and machine at an Air Force and produce the same documented results without

LONGERON

$A = 0.39\ in^2$

$I_z = 0.059\ in^4$

$I_y = 0.084\ in^4$

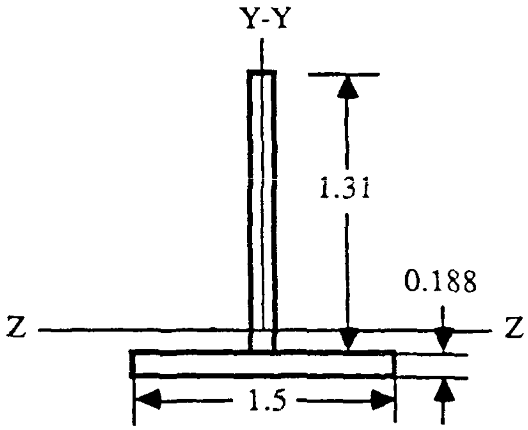


DOOR STIFFENERS

$A = 0.494\ in^2$

$I_z = 0.106\ in^4$

$I_y = 0.0536\ in^4$

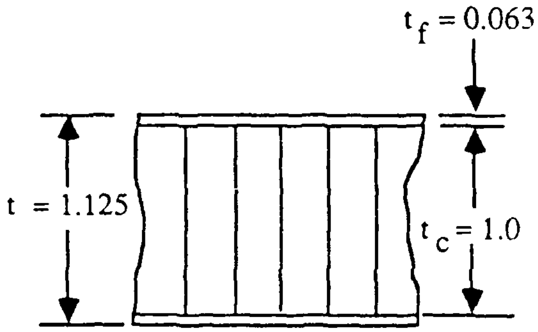


HONEYCOMB PLATE

$T = 0.126$

$12I / T^3 = 212.6$

$T_s / T = 0.125$



T = membrane thickness = $2t_f$

D = approx bending stiffness = $(E_f t_f t_c t) / (2(1 - \mu^2))$

T_s = transverse shear = $t_c G_c / G$

Figure 7-15. Cross Sectional Properties Documentation Example

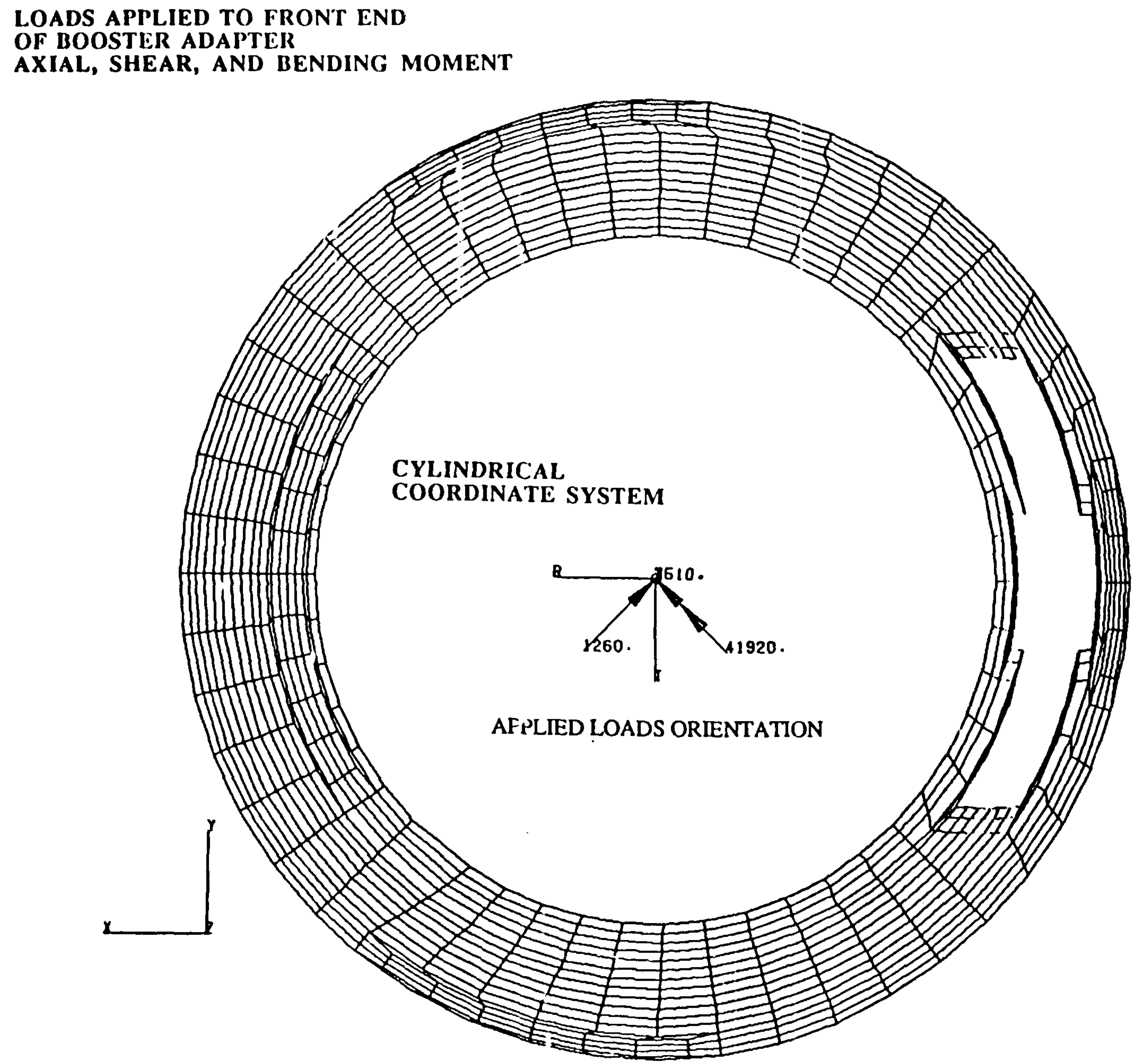


Figure 7-16. Finite Element Model Load Orientation Example

any modification to the file. Pre-processors are used industry wide to facilitate the generation of FEM. Therefore, along with the run deck should come the corresponding set of pre-processor neutral or universal files. If the modeler has input data to the run deck which would otherwise be there by translating the model using an available translator then these inputs should be documented. If it turns out that the non-supported code feature is a seldom used option, then the use of this feature should be explained and referenced as necessary. The restriction of FEM to COSMIC/NASTRAN format in the DID is very inefficient because conversion costs for a single model may be $450K as documented earlier. In addition, eight of ten AF organizations polled used MSC/NASTRAN. Most AF organizations had MSC/NASTRAN out of necessity because most contractors built their models with it. The DID analysis code format should be broadened to include at least MSC/NASTRAN for economic reasons.

The FEMs in the centralized database should include at a minimum all contractor generated FEMs along with the appropriate documentation. The FEMs generated by AF personnel could also be included in the system, but PDA feels that some sort of screening procedure should be implemented. Certain models could be used as benchmarks and learning tools. For example, ALC analysts may be able to use the modeling approach that another ALC used but not the specific model. Not all models could be reused or even used as examples and these should probably not be stored in a centralized system. Storage issues will become less of an issue as optical disks become in vogue. However, the detailed documentation required to enter a model into the database system for each FEM generated by the AF could be more costly than beneficial and might require more resources than the AF has available.

7.2 Costs of Centralized Database System

The costs associated with implementing a centralized database system can be divided into non-recurring and recurring costs. The initial startup costs will include software development, hardware purchases, and perhaps some facility allotment. The recurring costs will include personnel salaries and benefits, software leasing costs, hardware maintenance, and facilities costs such as utilities and telephone.

Initial cost of the system would include the development of software to address the unique features required for the manipulation of both narrative, graphics, and quantitative data relating to finite element models and their documentation. The proposed concept would take advantage of as much existing software as possible. Although this means that there will be yearly lease fees, PDA feels that it is preferable to have well supported software and reduce the amount of resources invested in software development. All of the technology presently exists to create a finite element database system. The majority of the software development costs will arise from developing a cataloguer system, user-interfaces, and communication interfaces. Perhaps the cataloguer system could be built around HYPERCARD or relational databases such as VAX RdB or RIM-5. It is

assumed that this initial development of a prototype system could be done within the scope of a SBIR Phase II budget ($ 500K).

Startup labor costs to load the existing models within the Air Force in the system would probably require the equivalent of four full-time staff members. A senior level engineer with some management abilities and two finite element analysts would be necessary to accomplish this initial task. There would also be a need for some clerical support. The salaries for the initial year of operation would be $ 400K.

Another initial cost, assuming that the centralized system would be a stand alone system because of security reasons, would be the purchase of hardware including CPU, graphics devices, tape drives, disk drives, and printer/plotter. Presently 70% of the AF organizations are using VAX systems so the proposed hardware for system is MICROVAX 3600. Table 7-1 summarizes the hardware components' costs proposed for this system.

The MICROVAX 3600 has 32 MB of memory, 622 MB disk, TK70 tape cartridge, and a year warranty and service as part of the standard package. Some additional DEC hardware needs are anticipated including an another 622 MB disk, 9 track 1600/6250 bpi tape drive, 2 monochromatic VT320 terminals. The large storage disks will allow significant amounts of data to be kept "on-line" simultaneously for FEM checkout. Peripherals for the system include a printer/plotter, and two graphics devices. A personal computer including software is included to handle the possible FEM catalogue information. (The GSA pricing for a initial license of DEC RDB is $ 16.9K not including annual maintenance costs which might make the personal computer a more economical approach.) Information can be transferred to the MICROVAX with communication software. A scanner and an optical disk storage system for permanent information are also included. The optical disk storage provides (1 GB per disk) for a large amount of data to be stored over an extended period of time without significant maintenance costs. If tapes are used to store data over the course of an aircraft's lifetime which may be as many as 30 years, there can be significant maintenance costs. Tapes must be cleaned at least once a year and be rewritten about every five years. The prices listed in Table 7-1 are base on GSA pricing (GS-00K88AGS-5918, discount agreement expires 30 Sep 1988) of current available equipment. The total price of the described system is $ 226.6K. Facilities costs should be minimal since a MICROVAX can be placed in an office environment and does not need a dedicated air conditioning system.

The major portion of the recurring costs will be salaries and benefits. In order to make this system cost effective, there can be no more than the equivalent of two and half full-time personnel on staff at the centralized database system. There will be a mix of talents required to operate this system successfully: (1) shipping/receiving clerk, (2) structural engineers, (3) computer systems person,and (4) a manager. Two full-time engineers should be ample to process FEM information after the initial setups are completed in the first year. The clerical, systems and managerial duties

Table 7-1. CENTRALIZED DATABASE SYSTEM HARDWARE PRICES

QTY	DESCRIPTION	PRICE ($ 1,000)
1	MICROVAX 3600 • 32 MB Memory • RA 82 - 622MB Disk • TK70 Tape Cartridge • 1 year field service and warranty	79.6*
1	RA82 - 622MB Disk	16.8*
1	TU81 - 9 Track, 1600/6250 bpi Tape Drive	21.8*
1	8 Line MUX RS 232	1.5*
2	VT320 Monochromatic Terminals, Cables	0.9*
1	8 User License, VMS	3.4*
1	VAX FORTRAN License	8.3*
	SUBTOTAL	**132.3**
1	Printer/Plotter	2.0
2	Graphics Devices	40.0
1	Emulex LX400 Optical Disk System	18.0*
20	1.0 GB Optical Disk	6.5*
1	Disk System Maintenance	2.8*
1	Scanner	5.0
1	PC and software	5.0
	TOTAL	**226.6**

* Prices are based on GSA pricing

should be support roles and could be covered by six manmonths of labor per year. Using the same assumptions for the cost of a fully burdened manyear of \$ 100K per year, the yearly salaries for the centralized database will be about \$ 250K per year. A prototype system may include the following commercially leased software: GEOMOD, PATRAN, and MSC/NASTRAN. These software packages were selected based on the frequency of use of these items in the USAF currently. Both GEOMOD and PATRAN lease prices include a two user option. GEOMOD cost could be reduced by "buying" their perrenial lease plus annual maintenance fees package. The potential annual recurring costs could be about \$ 350K (see Table 7-2).

The total startup cost for the centralized database system would be about \$ 1.1 million. The annual costs for the system after the first year of operation would be about \$ 350 K.

Preliminary cost estimates of this type tend to be understated because of hidden costs which emerge only as the system becomes better defined. Arbitrarily, it may be appropriate to increase both startup costs and annual operating costs by a factor of two. Even so, startup costs are less than 40% of the incurred costs that result from the present dispersed system and annual operating costs appear to be on the order of 10 to 15% of these costs.

Table 7-2. CENTRALIZED DATABASE SYSTEM ANUAL COSTS

DESCRIPTION	COST ($1,000)
2.5 Manyears Labor @ $ 100K/manyear	250.0
GEOMOD - 2 User License	39.0
PATRAN - 2 User License	19.5
MSC/NASTRAN	27.0
Hardware Maintenance and Extended Warranty	14.4
TOTAL	**~350**

7.3 Feasibility of a Centralized FEM System

Although an absolute cost for the ...nt system can not be determined because of the unknown variables. PDA feels that the ex... estimates for the present system are reasonable.

The cost for the centralized FEM system are based on the prototype system outlined earlier. The costs for this system should not vary substantially from the estimates.

Using the assumptions made in Section 6.0 there could be a yearly potential cost savings of between \$ 5M to \$ 10M. The yearly estimated operating costs for the centralized FEM system were on the order of \$350K-700K. These yearly savings could return the initial investment of the centralized system within the first year. The return on initial investments is conservative since the cost saving estimates were conservative. There is a definite possibility that the cost savings of a centralized system will increase as the capabilities of the finite element technique becomes more widely exploited through the USAF.

From the above arguments, a centralized FEM system appears to be feasible from a cost savings point of view. In addition there are other benefits which can be derived by having a well designed centralized system which are harder to quantify. These are intangible benefits such as: (1) FEM delivered to the Air Force once this system is installed should be more coherent and usable, (2) AF personnel should be able to exploit the knowledge of the engineers in industry more readily because of the sufficiently detailed documentation required, (3) scheduled time allotments for various tasks related to aircraft structural integrity could probably be reduced, (4) testing costs could be reduced and in some cases eliminated because of the availability of validated finite element models, (5) manpower costs used to specify FEM requirements and procure models after delivery could be reduced if AF standards such as those in the DID and section 4.1.3 are implemented, (6) increased reliability of the models used by the Air Force and delivered by the vendors, and (7) duplication of efforts could be minimized. PDA can not see any major disadvantage of a centralized system that would outway the benefits of such a system.

8.0 RECOMMENDATIONS AND CONCLUSIONS

The findings of this study indicated that a well designed centralized FEM system for finite element models of aircraft structures throughout the USAF should be implemented. There are many advantages to a centralized FEM system including cost savings potential and greater reliability of FEM delivered to the USAF. A conceptual prototype for a centralized database was described in Section 7. The initial hardware costs could be reduced significantly by installing such a system on existing hardware, if security issues are not a concern. No major disadvantages of a centralized system can be foreseen.

If for some reason the Air Force should delay the development of a centralized FEM system, PDA recommends that the Air Force should develop and implement contractual FEM deliverable standards as a minimal level of enhancement to the present system if the Air Force. These standards should use the DID as its foundations with additions recommended by the Phase I efforts. The implementations of AF standards are a necessary first step to building a effective centralized database. The development of deliverable standards could reduce some of the present system's costs by greatly reducing the effort to write contractual specifications, using standards written in a "boiler plate" format.

9.0 POTENTIAL APPLICATIONS

The centralized FEM system has potential applications in areas other than aircraft structures, for example missiles and ships. In fact, this approach can be used in any type of finite element model application. This type of system can be used in other military branches, governments agencies, or in industry. The details of the centralized FEM system, such as pre and post-processor and analysis codes, may require modification since other organizations use different finite element tools but the basic concept is applicable.

10. REFERENCES

1. 1987 CAD/CAM Industry Service. Dataquest, San Jose, CA.

2. Anon., "Navy CAD/CAM Second Acquisition, Request for Information Closure Document," Vol. 1, Developed with Input from the Navy and the Computer, Computer Graphics, and CAD/CAM Industry, Naval Sea Systems Command, Naval Air Systems Command, Naval Facilities Engineering Command, Naval Supply Systems Command, Space and Naval Warfare Systems Command, 22 May 1987.

3. Personal Discussions with David Branch, PDA PATRAN Sales Representative to McDonnell Douglas Corporation.

4. "Development of Structural Accelerated Geometric Editor ("SAGE"), Exxon Production Research Company, Contract No. PR-10769, January 1988.

5. G. Crose and H. E. Peck, Exploitation of Advanced X-Ray Computed Tomography Technology, Contract No. F33615-85-C-5026, AFWAL-TR-87-xxxx(Under Review).

6. H. M. Stoller, W. H. Pfeifer and R. L. Hack, "Assessment of Computed Tomography as an Improved Quantitative NDE Technique for Composite Materials", Contract No. F33615-86-C-5084, 87-PDA-FR-5335-00, May 1987.

7. "A Finite Element Expert System", A. J.Morris, College of Aeronautics, Cranefield Institute of Technology, Cranefield, England.

REFERENCES (continued)

8. "C-C Material Property Sensitivity Program" AFFTC, Edwards AFB., Contract No. F04611-86-C-0050, 1988.

9. Project Forecast II, AFSC-TR-86-006, June 1986, Volume III, Annex C, Technological Opportunities, Part 1, Knowledge-Based Systems [PT-36].

10. Olsen, J. J. and Venkayya, V. B., "Finite Element Models of USAF Aircraft Structures", Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Report No. AFWAL-TM-87-207-FIB, Nov 1987.

11. "Honeycomb Sandwich Design", Hexcel Products Inc., Brochure E, 1959.

12. "Honeycomb Sandwich, Design Data and Test Methods", Hexcel Products Inc., Brochure D, 1959.

13. Digital Equipment Corporation Quotation No. 880DNE0328, 26 Jan 1988, under GSA Contract No. GS-00K88AGS-5918.

14. Alestra, S. and Bennett R., "Force Management Technology Application Program Management at Sacramento Air Logistic Center", McClellan AFB, Feb 1987.

APPENDIX A

SURVEY OF USAF FINITE ELEMENT MODELING AND ANALYSIS OF AIRCRAFT STRUCTURES

ENGINEERING
2975 Redhill Avenue
Costa Mesa, California 92626
(714) 540-8900 Telex 683392

SURVEY OF USAF FINITE ELEMENT MODELING AND ANALYSIS OF AIRCRAFT STRUCTURES

NAME ______________________ DATE __________

ORGANIZATION ______________________________________

ADDRESS ______________________ PHONE __________

TECHNICAL BACKGROUND

TECHNICAL DISCIPLINE ______________________

JOB TITLE / POSITION ______________________

1. Years of experience

Years	Designer	Analyst	Manager	________
0 - 1				
1+ - 2				
2+ - 3				
3+ - 5				
5+ - 10				
10+ - 15				
15+ - 20				
20+				

2. Briefly describe the your organization's functions and responsibilities.

3. What area(s) of the design-analysis cycle are you involved in?

- ☐ preliminary design
- ☐ in-depth analysis
- ☐ final design
- ☐ testing
- ☐ other ______________________

4. What section(s) of the aircraft do you primarily work on?

FINITE ELEMENT MODELING LOGISTICS

5. List several applications for which you use or desire to use finite element models?

6. How many times a year do you need to obtain or generate finite element models?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 6 ☐ 12 ☐ ___

7. Who determines if there are finite element models that are available for your use?

☐ key contact person ☐ your superior ☐ you ☐ other ____________

8. If someone other than you determines the availability of FEM's, please specify that person by name,title, and affiliation:

   Name ______________________________
   Title ______________________________
   Organization _________________________
   Phone ______________________________

9. Are finite element models for your application readily available?

☐ Always ☐ Sometimes ___ % of time available ☐ Never

10. What factor determines if finite element models are not available for your use?

☐ lack of data
☐ cost
☐ inability to locate models in a reasonable time
☐ other ______________________________

11. If finite element models are available, how many sources must you normally contact to obtain the data?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 10 ☐ ___

12. Estimate the number of labor hours that are typically spent tracking down finite element model sources?

13. Once a finite element model is located estimate the turn around time between locating the model and actually obtaining the information at your site.

☐ 1 wk ☐ 2wk ☐ 3wk ☐ 1 mo ☐ 2 mo ☐ ____

14. Is there a fee associated with acquiring a finite element model ? If yes, then what is a typical fee?

☐ Always $______ Fee ☐ Sometimes $______ Fee ☐ Never

15. If a finite element model is available, does any documentation come with the model?

☐ Always ☐ Sometimes ___ % of time available ☐ Never

16. If documentation is available, does it include an explanation of the following items? Please check all boxes which are appropriate. Please expand on any doumentation features not covered by the categories listed below.

☐ FEM application (problem definition)
☐ list of elements and nodes which belong to a specific region (e.g., wing) of the model
☐ boundary conditions
☐ material properties
☐ other ____
____

17. If finite element model is available then what effort is required in order to use the model for your application? (Please check all which are applicable.) Also estimate the percentage of your time required to complete each effort.

	% of time
☐ convert the model into a format useable for your pre-processor	______
☐ modify geometry	______
☐ modify mesh	______
☐ change loads and/or boundary conditions	______
☐ change material properties	______
☐ run analysis application	______
☐ none (i.e., run "as is" on your software)	______
☐ other ____________________	______

18. If only the geometry data is available, what form is this data in ?

- ☐ drawings
- ☐ CAD/CAM files
- ☐ preprocessor files
- ☐ analysis input deck files
- ☐ other ____________

19. If finite element models are not available, can the geometry necessary for the your model usually be obtained?

☐ Always ☐ Sometimes ___ % of time available ☐ Never

20. How many sources must be contacted to obtain required model geometry?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 10 ☐ ___

21. How soon after a requirement for a finite element model is identified must the analysis be completed?

☐ 1 wk ☐ 2wk ☐ 3wk ☐ 1 mo ☐ 2 mo ☐ ___

22. In the current system, what is the major constraint which prevents or hinders you from developing you own finite element models?

☐ cost ☐ schedule ☐ manpower ☐ data ☐ other ____________

23. How often are modified configurations of existing aircraft tested instead of analyzed because of lack of finite element information?

☐ Always ☐ Sometimes ___ % of time tested ☐ Never

24. How often could you use ~~to~~ finite element analysis to augment testing?

☐ Always ☐ Sometimes ___ % of time ☐ Never

25. Estimate the elapsed time between definition of design modification of an existing aircraft configuration and test results for the "new" design.

26. List current job duties and responsibilities relevant to finite element modeling of structures in order of importance (1 = most important). Estimate the percentage of your total time you spend on each of the listed duties.

Importance Rank	Task Description	% of Time
1	______	______
2	______	______
3	______	______
4	______	______
5	______	______
6	______	______
7	______	______
8	______	______
9	______	______
10	______	______

FINITE ELEMENT MODELING TOOLS

27. What pre- and post- processors do you have access to?

☐ GEOMOD ☐ PATRAN ☐ Other ____________________

28. Which of the above pre- and post-processors have you used?

☐ GEOMOD ☐ PATRAN ☐ Other ____________________

29. What analysis codes do you use?

☐ ABAQUS ☐ Other (please list)
☐ ANSYS ____________________
☐ MSC/NASTRAN ____________________

30. What type of analysis do you do (Check all that apply)?

☐ structural static ☐ Other (please list)
☐ structural dynamic ____________________
☐ thermal ____________________
☐ aerodynamic ____________________
☐ acoustic ____________________

31. What computers are used in your finite element work?

32. Are the same machines used for the pre- and post-processing and the analyses?

☐ yes ☐ no

33. If the same machines are not used for pre- and post-processing and analysis then how is the data transferred between machines?

☐ magnetic tape ☐ network ☐ other ____________

34. Estimate the number of labor hours and elapsed time for data transfer between different machines?

_____ labor hours _____ elapsed time (hours)

35. What graphic devices do you use for pre- and post-processing?

36. What type of elements do you use in your modeling? Estimate the percentage of the time you use the following finite element types.

☐ beams ___ % of time ☐ plates ___ % of time ☐ solids ___ % of time

37. What type of loads do you apply to your models?

☐ pressures ☐ forces ☐ displacements
☐ thermal ☐ other ____________________

38. What is the nature of your loads?

☐ static ☐ time dependent ☐ frequency dependent ☐ other ________

39. Do you use the same material properties often?

☐ yes ☐ no

40. Would an "on-line" material properties database be useful for your applications?

☐ yes ☐ no

41. Check the following material property characteristics that you would like to be included in a material data base.

☐ isotropic ☐ orthotropic ☐ temperature dependent
☐ linearly elastic ☐ nonlinear elastic ☐ other ____________

DATA TRANSFER

42. List the groups and/or organizations from which you receive finite element modeling data?

43. In what format is your input data given to you from other groups?

☐ tabular listings ☐ computer files ☐ magnetic media
☐ other ______________

44. Is the input data given to you in the same format?

☐ Always ☐ Sometimes ☐ Never
___ % of time same format

45. List the groups and/or organizations to which you give finite element modeling data?

46. In what format is your output data given to other groups?

☐ tabular listings ☐ computer files ☐ magnetic media
☐ other ________________

47. Is the output data you give to other groups in the same format?

☐ Always ☐ Sometimes
___ % of time
same format ☐ Never

48. Do you process your data through some type of software translator which takes the data in its given format and rewrites it into a format useable for your application?

☐ Always ☐ Sometimes
___ % of time
used ☐ Never

49. What translators, if any, are you currently using?

TRANSLATOR NAME (e.g., PATNAS)	FUNCTION (e.g., change data from PATRAN format to MSC/NASTRAN format)
________________	________________________________
________________	________________________________
________________	________________________________

50. Specify in order of importance the translator features which are important for your applicatiom.

Importance Rank	Task Description
1	________________________________
2	________________________________
3	________________________________
4	________________________________
5	________________________________

51. If you do not use translators is it because

- ☐ data is not in a standardized format
- ☐ there are no translators availble for your application
- ☐ it is not feasible to use a translator for your application (please explain)

  ____

  ____

  ____

- ☐ other ____________________________________

  ____

  ____

52. Do you ever use substructuring?

☐ Always ☐ Sometimes ___ % of time ☐ Never

53. Do you ever have to transfer results (such as boundary conditions) from a finite element model to a submodel of that finite element model?

☐ Always ☐ Sometimes ___ % of time ☐ Never

54. What type of results are you interested in post-processing?

☐ displacements ☐ stresses ☐ strains
☐ temperatures ☐ other ____________

55. What form do you display your results in?

☐ contour plots ☐ deformed plots ☐ X-Y plots
☐ other ____________

DATABASE SYSTEM

56. Do you think a centralized database of finite element models would result in a more effective approach for conducting finite element analysis than the present method?

☐ yes ☐ no (please explain)

57. What would be the advantages of having some type of centralized finite element model database system?

- ☐ reduce time in obtaining finite element model information
- ☐ reduce inconsistencies in models
- ☐ quality control improvement
- ☐ reduce duplication of efforts
- ☐ other (please list)

____
____
____

58. How accessible would a finite element database have to be before you would use it?

- ☐ database must be resident on the computer you use in daily
- ☐ database available through a modem line
- ☐ database available through USAF organization via magnetic media
- ☐ other (please list)

____
____
____

59. What finite element model attributes should be used for cross referencing?

- ☐ aircraft manufacturer and model
- ☐ aircraft component (such as tail, wing, fuselage)
- ☐ date created, modified
- ☐ key contact individual (phone number, address)
- ☐ model application
- ☐ test result
- ☐ other (please list)

____
____
____

60. Prioritize the following database functions based on their importance to the completion of your finite element analysis application (1 - most important, 5 - least important).

Priority	Function
____	control and maintenance of FEM information
____	centralized location for FEM information
____	pre-processor standardization for FEM manipulation
____	standardized data exchange formats, translators
____	post-processing, management of results
____	other ______________________

61. List and discuss other important issues which are not covered by the survey.

APPENDIX B

DATA ITEM DESCRIPTION

DATA FOR FINITE ELEMENT MODELS OF AEROSPACE STRUCTURES

DATA ITEM DESCRIPTION	Form Approved OMB No. 0704-0188 Exp Date: Jun 30, 1986

1. TITLE	2. IDENTIFICATION NUMBER
Data for Finite Element Models of Aerospace Structures	

3. DESCRIPTION/PURPOSE

This report describes the data elements and the format of the finite element models of aerospace structures to be delivered to the Air Force. This data will be used to verify the contractors structural analysis and/or to determine the effects of future modifications (or changes) to the structure or its operational conditions. It should be noted that not all the data items will be applicable to every system. The applicable items will be identified on a CDRL (DD Form 1423).

4. APPROVAL DATE (YYMMDD)	5. OFFICE OF PRIMARY RESPONSIBILITY (OPR)	6a. DTIC REQUIRED	6b. GIDEP REQUIRED

7. APPLICATION / INTERRELATIONSHIP

The finite element data generated for verifying the structural design criteria of an aerospace vehicle (designed and paid for by the Air Force) should be be the property of the Air Force and should be delivered in a suitable and understandable form for future use. This data will be extremely valuable in assessing the integrity of the system after modifications, repairs and maintenance.

8. APPROVAL LIMITATION	9a. APPLICABLE FORMS	9b AMSC NUMBER

10. PREPARATION INSTRUCTIONS

10.1 General Requirements. The finite element data supplied in response to this CDRL item must accompany a problem narrative. This narrative must include the following items:

- Configuration version.
- Identification of the documents and/or drawings from which the model was generated. Copies of these documents must be provided if they are not available to the government.
- A key diagram showing the location of the component being modeled in relation to the rest of the structure.
- A brief description of the physical phenomena being modeled.
- A discussion on the coarseness/fineness of the grid selected.
- A rational explanation for the elements selected for the model.
- An explanation of the boundary conditions.
- Materials - Identification of the Mil Standard from which the mechanical properties were derived. Reasons for any deviations from the standard properties.
- A complete description of the flight maneuvers for which the loading conditions are attributed.
- Planform used for aerodynamic analyses showing all important dimensions.

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U.S. Government Printing Office: 1985-[illegible]

10.2 Analysis Data Requirements. The finite element analysis models are classified into the following five categories:

I. Static Analysis Models

II. Dynamic Analysis Models

III. Aeroelastic Analysis Models

IV. Heat Transfer Analysis Models

V. Acoustic Cavity Analysis Models

The CDRL will call for the specific models required.

10.2.1 Static Analysis Model Requirements. A static analysis basically requires a good stiffness representation. However, when gravity loading or inertia relief conditions are specified, a good mass representation is also required. This mass representation must include both structural and nonstructural mass distributions. The finite element models for static analysis must consist of the following items as a minimum.

i) Geometry - (as appropriate)

Grid Point Coordinates
Element Types
Element Connections
Coordinate Systems

ii) Element Properties - (as appropriate)

Thicknesses
Cross-sectional Areas
Moments of Inertias
Torsional Constants
Fiber Orientations
Other properties as required for special elements.

iii) Material Properties - (as appropriate)

Isotropic
Anisotropic
Fiber Reinforced Composites
Temperature Dependent Properties
Stress Dependent Properties
Thermal Properties
Damping Properties
Other properties as required for special problems.

iv) Boundary Conditions - (as appropriate)

Single Point Constraints
Multipoint Constraints
Partitioning for Reduction or Substructuring

v) Loading - (as appropriate)

Static Loads
Gravity Loads
Thermal Loads
Centrifugal Loads
Other loading conditions as required for special simulations.

For buckling or nonlinear analysis additional information is required on the following items:

- How the nonlinear matrices are derived.

- The method of solution for the nonlinear problem.

- A description of the method in the case of an eigenvalue analysis.

10.2.2 Dynamic Analysis Models. The dynamic analysis models require i) geometry, ii) element properties, iii) material properties, and iv) boundary conditions as described for the static case. In addition an accurate nonstructural mass and damping representation is required. Generally five types of dynamic analysis are contemplated.

- Normal Modes Analysis or

- Complex Eigenvalue Analysis

- Frequency Response Analysis

- Transient Response Analysis

- Random Response Analysis

In the first two cases only the method of eigenvalue analysis and the frequency (modes) range of interest need be specified. For frequency response analysis the frequencies of interest must be specified. For transient response analysis the dynamic load must be defined as a function of time or must be provided as tabular values. For random response analysis the statistical nature of the input (such as PSD, Auto Correlation) and the statistical quantities of the output desired must be specified. In addition all the information on dynamic reduction and/or modal reduction must be specified.

10.2.3 Aeroelastic Models. An aeroelastic analysis requires mathematical models of the structure and the aerodynamics. The structure is generally represented by finite element models (FEM). The requirements for the structures models are as specified under static and dynamic analysis. They include mass, stiffness and damping representation. Both structural and nonstructural mass distributions shall be included in the mass model. The aerodynamic models are generally based on paneling or equivalent methods. The requirements of the aerodynamic models are those of the panel geometry which cover all the lifting surfaces including the control surfaces, the empennage (horizontal and vertical tails) and canard surfaces. The fuselage slender body and interference panels shall be modeled to represent the flowfield adequately. The altitude (air density), mach number and other relevant aerodynamic parameters must be specified. The details of the aerodynamic theory and the limits of its validity must be clearly defined. In addition, data for the force and displacement transformations from the structural grid to the aerodynamic grid (and vice versa) shall be included in the aeroelastic models. Two types of aeroelastic analysis are contemplated. Both deal with the phenomenon of aeroelastic stability. The real eigenvalue analysis is the basis for determining the static aeroelastic stability. There are a number of methods for determining

dynamic aeroelastic stability (flutter analysis), and the details of the method (references) and the necessary data shall be provided with the models. Flutter analysis is generally an iterative process and can also involve more than one flutter mechanism. There are often special techniques associated with the flutter analysis, and they can be defined in terms of the ranges of the aerodynamic parameters. Such data shall be included in the aeroelastic models. In addition, provisions must be made to include the effects of the rigid body modes on the flutter model (body freedom flutter). If it is anticipated that these models will be used for aeroservoelastic analysis, then the data shall be provided for a state space formulation. Also sensor actuator locations and their range of operation and/or limitations shall be included in the data. In addition, a flight control system block diagram shall be provided with sufficient information to define all transfer functions and gains using S-domain variables for analog systems or Z-domain variables for digital systems. The units of important parameters shall be provided.

10.2.4 <u>Heat Transfer Analysis Models</u>. There are three elements to heat transfer models: the heat conducting medium, the boundary conditions and the heat sources and/or sinks. The data requirements of the heat conducting medium are similar to those defined for static and dynamic analysis. For instance the geometry definition includes the grid point coordinates, element types, element connections and coordinate systems. Elements can be classified into volume heat conduction and surface elements. The element type designation for the volume heat conduction element is generally derived from the degree of approximation of its shape functions. The surface elements are used to model a prescribed heat flux, a convective flux due to the difference between the surface temperature and the recovery temperature or local ambient temperature, and radiation heat exchange. Appropriate material properties, single point and multipoint boundary conditions and description of the heat sources (applied forces) have a similar correspondence in the static and/or dynamic analysis. The surface heat convection or radiation details shall be provided (through surface elements) as appropriate. The response variables in heat transfer analysis are generally grid point temperatures or the temperature gradients and heat fluxes within the volume heat conduction elements and the heat flow into the surface elements. Four types of heat transfer analysis are contemplated:

i) Linear Steady-State Response Analysis

ii) Linear Transient Response Analysis

iii) Nonlinear Steady-State Response Analysis

iv) Nonlinear Transient Response Analysis

It is often necessary to adopt special techniques for obtaining stable solutions, particularly in the last two cases. The data pertaining to these special techniques and the limitations of the nonlinear algorithms shall be fully identified.

10.2.5 <u>Acoustic Cavity Analysis Models</u>. Basically there are three elements in acoustic cavity analysis models: the acoustic medium, the boundaries, and the sources of excitation. The acoustic medium model shall consist of grid points and acoustic elements connecting these grid points. The response variables are generally the pressure levels and the gradients of the pressures (with respect to the spatial variables) at the grid points. So for a general three dimensional acoustic analysis there will be four degrees of freedom per node (corresponding to four response variables) in an acoustic medium model. The properties of the acoustic medium can vary with the temperature and pressure distribution and density. The boundaries of the acoustic model can be solid walls, flexible walls, openings in the walls and walls with acoustic material which can be represented as a complex acoustic impedance. For complicated boundary conditions separate finite element models may be necessary in order to derive the boundary conditions for the acoustic model. These finite

element models are based on solid mechanics and their data requirements are similar to those described for the static and dynamic analysis earlier. The acoustic excitation source model shall have information on the spatial distribution and the statistical properties (in terms of the frequency content) of the noise. For a deterministic case, however, definition of the forcing function includes the magnitude, phasing and frequency along with the spatial distribution. The acoustic excitation is generally given as velocity or pressure applied to the medium over prescribed surfaces or at grid points. If the disturbance is from mechanical sources, separate finite element models of the sources shall be supplied as required. These models are also generally solid mechanics models and their requirements are similar to static and dynamic analysis models. Generally three types of acoustic analysis are contemplated.

- Eigenvalue Analysis
- Steady-State Solution
- Nonlinear-Analysis

In the eigenvalue analysis the acoustic natural frequencies and mode shapes are determined. The purpose is to compare the natural frequencies of the cavity with those of the forcing function and estimate the resonance effects, and to compare the natural frequencies to the resonant frequencies of any structure which may be placed in the cavity. This analysis provides useful information for design changes in the cavity either by altering the overall dimensions or by introducing noise suppression mechanisms such as baffles or by adding noise suppression material to introduce acoustic wall impedance. This analysis does not require explicit definition of the forcing function. The steady-state solution gives the response of the cavity to a given excitation. This analysis can be in the time or frequency domain. The nonlinear analysis involves an iterative solution when the properties of either the cavity or the acoustic medium vary significantly with the pressure levels and/or temperature.

10.3 <u>Other Requirements</u>.

The input data for all the finite element models must be provided in a format compatible with the latest government version of NASTRAN (COSMIC/NASTRAN). If the original analysis was made with another finite element program, the data shall be converted to the COSMIC/NASTRAN format. If NASTRAN does not have compatible elements or capability, the elements that are most appropriate must be identified and projections must be provided on the expected differences.

In addition to the input data a summary of output results (such as deflections, stresses, frequencies, etc. at critical areas) shall be provided for future validation of the models. Also a brief description of how these results were used to satisfy a specific design criteria. A set of undeformed and deformed plots of the structure shall be provided with all the finite element models.

For Details Contact

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